Defense Science Board
Task Force
on
Directed Energy Weapons

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Office of the Under Secretary of Defense
For Acquisition, Technology, and Logistics
Washington, D.C. 20301-3140

OFFICE OF THE SECRETARY OF DEFENSE
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WASHINGTON, DC 20301-3140

DEFENSE SCIENCE
BOARD

26 Nov 2007

MEMORANDUM FOR UNDER SECRETARY OF DEFENSE FOR ACQUISITION, TECHNOLOGY, AND LOGISTICS

SUBJECT: Final Report of the Defense Science Board Task Force on Directed Energy Weapon Systems and Technology Applications

I am pleased to forward the final report of the Defense Science Board Task Force on Directed Energy Weapons Systems and Technology Applications. This study is the second of its kind conducted by the Board, who in 2001, also reviewed directed energy weapons programs in DOD.

Similar to the conclusions of the earlier study, this task force believes that directed energy offers tremendous promise in improving operational capabilities to conduct certain missions. The potential of these systems is such that the Department should increase the attention paid to the scope and direction of the efforts underway today. Even after many years of development, there is not a single directed energy system fielded today, and fewer programs of record exist than in 2001. This circumstance is unlikely to change without a renewed focus on this important area.

The task force offers a set of recommendations that would help the Department better position itself for successful development and deployment of operational directed energy systems. I endorse all of the study's recommendations and encourage you to forward the report to the Secretary of Defense.

Dr. William Schneider, Jr.
DSB Chairman

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DEFENSE SCIENCE BOARD

MEMORANDUM FOR CHAIRMAN, DEFENSE SCIENCE BOARD

SUBJECT: Report of the Defense Science Board Task Force on Directed Energy Weapon Systems and Technology Applications

Directed energy offers promise as a transformational "game changer" in military operations, able to augment and improve operational capabilities in many areas. Yet despite this potential, years of investment have not resulted in any operational systems with high energy laser capability. The lack of progress is a result of many factors from unexpected technological challenges to a lack of understanding of the costs and benefits of such systems. Ultimately, as a result of these circumstances, interest in such systems has declined over the years.

This task force was asked to review all directed energy programs in the Department and other organizations as well as supporting technology advancements and their applications. This report contains the results of that review and provides a window into the progress toward weaponization of these systems.

While the task force heard descriptions of dozens of technically feasible and operationally relevant directed energy programs and activities, the report focuses on a smaller number of the most promising applications. Applications with potential to provide superior capabilities include long-range strategic missions such as space control and force protection, and tactical missions such as ground-based defense against rockets, artillery, and mortars and defense against man portable air defense systems. For some applications, directed energy has the potential to compete favorably with kinetic solutions; for others, no adequate kinetic approach currently exists.

The task force believes that the range of potential applications is sufficient to warrant significantly increased attention to the scope and direction of efforts to assess, develop, and field appropriate laser, microwave, and millimeter wave weapons. But until the operational demand generates priorities, there is little reason to expect rapid progress in fielding such systems. Further, the currently fragmented science and technology projects and programs must be directed to research and development programs leading to fielded systems. The task force believes that the Department can take the following steps to better position itself for successful development and deployment of operational directed energy systems.

- Directed energy employment needs to be clearly described in concepts of operation as the basis for decisions relating to technical, employment, policy planning and priorities.

- For each capability gap where directed energy is a proposed solution, the directed energy solution should be assessed against available kinetic or other approaches to filling the gap.

- Research and development funding should be focused on those directed energy solutions where rigorous analyses identify directed energy as the most promising solution to a priority need and concentrated for progress rather than spread over a large number of projects.

- S&T funding for laser weapons should be heavily focused on high power solid state and fiber lasers and significantly improved beam control for appropriate applications and on concentrated development of free electron lasers for ship defense.

- The Department needs an authoritative single source data base for directed energy effects similar to the munitions effects manual for kinetic weapons.

- The development of laser and high power microwave technologies and systems available to potential adversaries poses a new set of challenges to U.S. military force capabilities which must be better understood and tracked.

- The Department needs a concerted education effort to replace the "death ray" myth of directed weapons with a comprehensive understanding of the potential benefits and limitations of their application.

We appreciate the contributions of all those involved in this effort: the members of the study; the government advisors; our executive secretaries Col Jim D. Wallace II, USAF Reserve and Dr. Thomas Spencer; Maj Charles E. Lominac II, military assistant; and staff analyst, Mr. Anthony L. Johnson.

General Larry D. Welch
Co-Chair

Dr. Robert J. Hermann
Co-Chair

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Executive Summary

The Potential

Directed energy continues to offer promise as a transformational "game changer" as the Department of Defense (DOD) encounters new asymmetric and disruptive threats, while facing increasingly sophisticated traditional challenges. Yet years of investment have not resulted in any currently operational high-energy laser capability. In addition, the single high-energy laser program of record, the Airborne Laser (ABL) for boost phase missile defense, continues to experience delays and potential budget reductions.

There is a strong belief in the directed energy community, and in segments of the warfighter and force-provider communities, that high-power microwave (HPM) offers capabilities in anti-sensor applications and as non-lethal weapons. Still, HPM advancement has been limited by uncertainty about its effects and effectiveness.

Years of major investment in chemical lasers has produced megawatt-class systems that could have a wide range of applications. However, size, weight, and logistics issues limit them to integration on large platforms, such as the 747 used for the ABL program, or fixed ground applications such as the Ground-Based Laser for Space Control. As a consequence, interest in these systems and expectations of progress has significantly decreased.

The current focus is on solid state lasers with the promise of providing for smaller, lighter systems with deep magazines. However, the current goal for solid state laser development would provide a power level more than an order of magnitude lower than current chemical lasers. While beam quality and other factors can compensate for some of the difference in power level, there is currently little investment in those aspects. Further, these cannot make up the delta in power of chemical vs. solid state lasers. The near-term projection for solid state lasers is a power level closer to two orders of magnitude below that of chemical lasers. A major increase in investment is required—perhaps of the same order as the previous investment in chemical lasers—to realize the potential of solid state lasers.

Even considering the reduced power levels, electrically based solid state and fiber high-energy laser (HEL) technologies, with improving efficiency and power levels, could, with time and investment, enable transportable "tactical" applications on aircraft, ground vehicles, and ships. Free electron lasers, with the promise of high power, high beam quality, and wavelength agility could offer unique advantages for ship-based applications.

At medium power levels, solid state laser systems with improved efficiency and reasonable beam quality could provide manned and unmanned aircraft applications at power levels of tens to hundreds of kilowatts for self-defense and, eventually, precision ground attack.

Advances in electrically based solid state and fiber lasers have produced low-power applications with higher power applications achievable within a few years, given adequate direction and investment. These include less than lethal applications at power levels ranging from less than a watt to 10s of watts of average power. Technology prospects, applications, and issues for laser power are discussed in Chapter 2 of this report.

High-power microwave and millimeter wave system developments have provided prototype capabilities currently in use in combat operations. Further, there are promising applications that address identified current gaps in capability. Specific discussion of microwave technologies, applications, and issues is found in Chapter 3 of this report.

The Record and Obstacles

In spite of the promise, delivery of high-power laser capabilities remains a potential for the future. In June 2001, the Defense Science Board provided a comprehensive assessment of the state of laser technologies in its report *High Energy Laser Weapon Systems Applications,* which addressed, among other tasks, "what remains to be done to 'weaponize' these systems." At that time, there was high interest and optimism for future progress, based on a number of ongoing programs that were expected to produce fielded capabilities within five to twenty years, including:

- The Airborne Laser's critical operational demonstration has slipped almost year for year since that report was published.
- The Space-Based Laser for missile defense has been effectively abandoned.
- The Tactical High Energy Laser (THEL) program to provide battlefield capabilities for ground forces was terminated.
- Maritime Self-Defense, the Free Electron Laser, is still in the technology development phase.
- The Airborne Tactical Laser (ATL), undergoing an extended user evaluation at the end of a successful advanced concept technology development (ACTD), is not a program of record.
- The Ground-Based Laser for Space Control is not currently being pursued.
- The Tactical High Energy Laser Fighter is no longer a projected program, but could be an evolution of the ATL ACTD.
- Future Combat Systems applications are no longer part of the Future Combat System program.
- Laser blinding of guidance systems of air-to-air missiles has been demonstrated but not fielded.

With this disappointing lack of progress, there has been a marked decline in interest on the part of operational customers, force providers, and industry. There are multiple reasons for the lack of current progress and perceived promise of directed energy, including unexpected challenges in developing the technology and lack of priority. The most fundamental issue affecting priority for developing and fielding laser and microwave/millimeter wave systems useful to combatant command missions is the need for cost-benefit analyses supporting priority choices. Such analyses require a coherent and consistent means of evaluating and reporting laser and microwave/millimeter wave system effects that, to date, have not been a rigorous element of the programs and projects.

The need for such analyses is exacerbated by two underlying issues. The first is that directed energy, in general, suffers from a history of overly optimistic expectations. For example, in the early 1970s, an Air Force decision to cancel a short range air-to-air missile program was strongly influenced by the projection that, with increased focus and funding, the need could be filled in the near term with laser weapons suitable for fighter aircraft. Almost 30 years later, there is little prospect of achieving such a capability. More recent examples, mentioned above, are the multiple years of delay on the well-funded ABL program and the demise of the otherwise successful THEL program for programmatic issues, including logistic complexity on the battlefield.

A second issue is that, for many proposed applications, there are competing and well-understood conventional approaches to producing the desired effect. Given the history of high-energy laser programs, these conventional approaches are more credible to warfighters and force providers.

The lack of adequate cost-benefit analyses and focused mission analyses inhibits the effective use of currently programmed resources for directed energy development with over half the total DOD investment going into a single system—the Airborne Laser—with emphasis on a currently unproven mission capability of boost phase intercept of ballistic missiles.

Some Promising Applications

The task force heard impressive descriptions of dozens of directed energy programs and activities, many of which seemed technically feasible and operationally relevant. Still, given the generally low level of operational user needs assessment relevant to directed energy applications, it was not useful to fill this report with descriptions of the many activities currently underway. Instead, the focus is on a smaller number of promising applications that stood out, each supported by any number of activities, but few being pursued on a defined path to operationally useful fielded capability.

The task force did conclude that there are a number of promising applications of directed energy. For some of the applications, directed energy has the potential to compete favorably with kinetic solutions. For others, the task force found no adequate kinetic approach. While the process of choosing priorities for funding and emphasis should include rigorous cost-benefit analyses, the following have the potential to provide superior, and in some cases unique, capabilities:

- Long-range strategic missions for HEL application
  - Space control
  - Force protection
- Tactical missions for HEL application
  - Ship defense against maneuvering cruise missiles and tactical ballistic missiles
  - Ground-based defense against rockets, artillery, and mortars
  - Ground-based capability to destroy adversarial unmanned aerial vehicles
  - Airborne defense of aircraft against man-portable air defense systems (MANPADS)
- Tactical missions for HPM
  - Ground-based vehicle stopping system
  - Airborne defeat of MANPADS
  - Vehicle mounted defeat of implanted improvised explosive devices (IEDs)
  - Airborne defeat of electronic systems
- Tactical missions for high-power millimeter wave
  - Ground-based active denial system

While the above list is neither exhaustive nor adequately assessed, it should be enough to warrant significantly increased attention to the scope and direction of efforts to assess, develop, and field appropriate laser, microwave, and millimeter wave weapons. There is little reason to expect rapid progress in fielding high-power laser or high-power microwave weapons until operational demand generates priorities, and until the currently fragmented science and technology (S&T) projects and programs are focused on moving to research and development programs leading to fielded systems.

Organization

There is an extensive array of organizations within the Department with roles and responsibilities for aspects of directed energy work. Appendix D provides a description of a number of those organizations and their roles. The task force did not find compelling reasons to reorganize. The report includes recommendations intended to focus the current organizations more effectively on activities consistent with currently assigned roles and responsibilities.

Legal and Policy Aspects

The task force heard concerns over the legal and policy aspects of employing directed energy weapons. The concern is seen by some as inhibiting or deterring development of such weapons with reluctance to invest in capabilities that might not be useable in the battlespace due to legal or policy constraints. Much of this concern is the product of inadequate communications rather than any unusual legal or policy constraints.

The Office of the Secretary of Defense and service component Judge Advocate General Offices have determined that directed energy weapons are, in and of themselves, legal according to all U.S. laws, the Laws of Armed Conflict, and are consistent with all current U.S. treaty and international obligations. Noting that directed energy weapons are legal does not imply that their use in a particular situation is legal. There are situations where the use of a directed energy weapon could be contrary to U.S. or international law. This consideration is the case with virtually any weapon.

One such constraint is the use of a laser weapon to intentionally blind combatants. The States Parties to the 1980 Convention on Prohibitions or Restrictions on the Use of Certain Conventional

Weapons Which May Be Deemed to be Excessively Injurious or to have Indiscriminate Effects had a fourth protocol adopted in 1995, where the intent is to prohibit laser weapons that are specifically used to blind combatants systematically and intentionally.[1] While the United States is not a signatory to this particular protocol, the DOD has issued a policy that prohibits the use of lasers specifically designed to cause permanent blindness of unenhanced vision.

That same policy stated that "…laser systems are absolutely vital to our modern military. Among other things, they are currently used for detection, targeting, range-finding, communications, and target destruction. They provide a critical technological edge to U.S. forces and allow our forces to fight, win, and survive on an increasingly lethal battlefield. In addition, lasers provide significant humanitarian benefits. They allow weapon systems to be increasingly discriminate, thereby reducing collateral damage to civilian lives and property. The [DOD] recognizes that accidental or incidental eye injuries may occur on the battlefield as the result of the use of legitimate laser systems. Therefore, we continue to strive, through training and doctrine, to minimize these injuries."

A similarly supportive policy has been stated for other directed energy weapons. At the same time, when such weapons are new to the battlespace, there will be a policy determination on their initial introduction to include an understanding by appropriate policy makers of the intended uses. Such determination needs to be informed by a thorough and credible understanding of the risk and benefits of employing such weapons. Beyond the process of approving first use, the expectation is that the Laws of Armed Conflict, rules of engagement, and combat commander direction will govern employment of directed energy weapons as is the case for kinetic weapons.

1. W. Hays Park, Special Assistant for Law of War Matters, Department of the Army, Office of the Judge Advocate General, Memorandum of Law, DAJA-IO (27-1a), 20 December 1996.

Bottom Line Findings and Recommendations

- Directed energy employment needs to be clearly described in concepts of operation as the basis for decisions relating to technical, employment, policy planning, and priorities.
  - *The Under Secretary of Defense for Acquisition, Technology and Logistics (USD [AT&L]) should require that the military departments provide a concept of operation for each proposed laser and HPM weapons system.*
- For each capability gap where directed energy is a proposed solution, the directed energy solution should be assessed against available kinetic or other approaches to filling the gap.
  - *USD (AT&L), the Director, Program Analysis and Evaluation, and the military departments should establish programs analyzing the cost and benefit of promising applications of laser and HPM weapons to fill identified capability needs.*
- Research and development funding should be focused on those directed energy solutions where rigorous analyses identify directed energy as the most promising solution to a priority need and concentrated for progress rather than spread over a large number of projects.
  - *USD (AT&L) should task the military departments to provide road maps (strategic plans) to move demonstrated technologies to fielded capabilities in accordance with priorities established by combatant commands and force providers.*
- S&T funding for laser weapons should be heavily focused on high power solid state and fiber lasers and significantly improved beam control for appropriate applications and on concentrated development of free electron lasers for ship defense.
  - *The Director, Defense Research and Engineering, should give high priority to S&T activities addressing high power solid state laser development and accompanying beam quality and beam control development.*

- The Department needs an authoritative single source database for directed energy effects similar to the munitions effects manual for kinetic weapons. Development of meaningful concepts of operations and analyses of military utility require the foundation of credible weapons effects data and assessments.
  - *The Deputy Secretary of Defense should assign responsibility to a military department to develop a laser and high power microwave effects manual.*
- The development of laser and high power microwave technologies and systems available to potential adversaries poses a new set of challenges to U.S. military force capabilities.
  - *The Under Secretary of Defense for Intelligence (USD [I]) should:*
    - *Produce a needs statement for the national intelligence community that details the information support that is required to perform quality threat assessment and identify development opportunities and needs.*
    - *Designate a member of the USD (I) staff to be a focal point for advocating improvement in all dimensions of directed energy intelligence.*
  - *The Director, Defense Intelligence Agency, should undertake a specific program to discover and assess emerging laser and high-power microwave capabilities available to the full range of potential adversaries. The program needs to be supported by people with expertise in directed energy technologies and applications.*
- The Department needs a concerted education effort to replace the "death ray" myth of directed weapons with a comprehensive understanding of the potential benefits and limitations of low-, medium-, and high-power laser applications, high-power microwave, and millimeter wave applications.
  - *The military departments should accelerate efforts to credibly assess effects on human targets, and widely publicize the facts.*

Chapter 1. Threat

The continuing transformation of U.S. defense forces has produced new and highly effective military capabilities. At the same time, this transformation can expose new vulnerabilities that can be exploited with directed energy weapons that are within the technological capabilities of a variety of potential adversaries.

This unclassified chapter does not attempt to describe specific threats or ascribe threat capabilities to specific potential adversaries. Instead the focus is on inherent vulnerabilities relevant to directed energy applications. U.S. and allied military operations are increasingly dependent on surveillance and reconnaissance assets to make decisions that are essential to effective operations.

Advanced kinetic weapon systems have been and still are in development in a number of nations and the proliferation of those systems to a wide range of nations and non-state organizations has increased significantly over the past 15 years. A number of these entities have openly published critiques of U.S. military operations from the Balkans to Iraq and Afghanistan. The observations point to the lesson that the U.S. military has large tactical battlefield advantages that anyone that wishes to oppose us must solve if they are to have any chance for success. Directed energy weapons technology is accessible to a wide range of potential adversaries and represents a means for potential adversaries to seek military advantage.

The international offensive weapons trend facing the United States and its allies will include a combination of greater speed, improved signature reduction, integrated employment of decoys, and sophisticated deception. The new weapons are intended in sum to compress the time available for effective reaction. Defensive systems that address the compressed reaction time problem can negate deception and decoy employment. These systems, which are capable of dealing with swarming tactics, present the most effective counter to emerging threats. The calculus of the relative advantages of kinetic and directed energy defensive systems will need to be continuously reevaluated as these new developments emerge.

U.S. dependence on force-enabling capabilities in command and control, information management, advanced sensors, and support systems are recognized around the world. It would be prudent to assume that future enemies intend to take on these enabling factors. In many cases current and projected systems have inherent vulnerabilities and inadequate defensive features. They are particularly susceptible to the types of directed energy systems that are believed to be feasible for a wide range of potential adversaries. It will be essential to have substantial operational experience in directed energy weapons capabilities to adequately assess threat impacts on U.S. and coalition operations.

As examples, laser systems that could disable space-based and airborne sensors—either permanently or temporarily—are available to potential adversaries to include non-state actors. Increased design attention to protection against these capabilities is needed.

Similarly, high-power microwave technologies that can be exploited to damage or disable electronic components of essential communications networks are available to a range of potential adversaries, including non-state actors. Investment in approaches that provide increased robustness in essential networks is needed to preclude denial of these capabilities.

Defensive directed energy systems should be attractive to a number of potential adversaries whose strategies are oriented toward negating the effectiveness of U.S. and allied offensive power. Systems that can be relocated, though not necessary mobile, are suitable for employment in defending relatively small geographic regions from airborne threats. It should be expected in the coming decade that the United States will have to deal with a number of directed energy systems developed along these conceptual lines. Current technology favors the use of directed energy weapons in a defensive strategy, where a ready re-supply of consumables and adequate power facilitate operations.

Intelligence on the global trend in all forms of weapons systems development needs to be considered an integral part of the U.S. directed energy program. The end of the cold war and the attention paid since the mid-1990s to immediate problems of international unrest and the global war on terrorism have diverted attention from scientific and technical intelligence. The national and tactical intelligence gathering and analytic communities should substantially increase the emphasis on knowing with higher certainty the threats faced by the United States and the technology achievements that could alter the strategic balance. Current work is by too few people, with inadequate budgets, insufficient technical collection capabilities, and fragmented connection to the directions and achievements of U.S.-directed energy programs.

Findings and Recommendations

- The development of laser and high-power microwave technologies and systems available to potential adversaries poses a new set of challenges to U.S. military force capabilities.
  - *The Under Secretary of Defense for Intelligence (USD [I]) should:*
    - *Produce a needs statement for the national intelligence community that details the information support that is required to perform quality threat assessment and identify development opportunities and needs.*
    - *Designate a member of the USD (I) staff to be a focal point for advocating improvement in all dimensions of directed energy intelligence.*
  - *The Director, Defense Intelligence Agency, should undertake a specific program to discover and assess emerging laser and high-power microwave capabilities available to the full range of potential adversaries. The program needs to be supported by people with expertise in directed energy technologies and applications.*
- Space-based and airborne sensor development programs and communications satellites should include protection against laser systems that can dazzle or destroy sensor capabilities.
  - *The Secretary of the Air Force; the Commander, Air Force Space Command; and the Director, National Reconnaissance Office should require a full analysis of the survivability of essential space-based*

capabilities assuming adversary capabilities to attack satellites with directed energy weapons.

- Electronic components of essential communications networks are susceptible to damage and disruption from high-power microwave systems.
  - *The Assistant Secretary of Defense for Networks and Information Integration (ASD (NII)) and the Director, DISA, should require a full analysis of the survivability of essential communications networks assuming adversary capabilities to attack electronic components with directed energy weapons.*
  - *The Under Secretary of Defense for Acquisition, Technology and Logistics (USD (AT&L)) should direct that:*
    - *New systems include protection against high power microwave disruption.*
    - *The ASD (NII) should direct an assessment of the feasibility of protecting existing command and control networks against directed energy attacks.*

Chapter 2. High-Energy Laser Technology and Programs

This chapter assesses the status of high-energy laser (HEL) programs; developments; and technology, subsystem, and prototype demonstrations that have occurred since the baseline established in the June 2001 Defense Science Board (DSB) study. In addition, this chapter also examines what remains to be accomplished to identify and follow logical and coherent paths for system development.

The long-cited advantages of HEL include speed of light response, precision effects, limiting collateral damage, deep magazines, and low cost per kill. The potential HEL missions of boost phase missile defense and ship self-defense can be supplemented with near-term applications that can now be achieved with lower power.

Electrically based solid-state and fiber lasers with improved efficiency and power levels have enabled transportable "tactical" applications on aircraft, ground vehicles, and ships. Free electron lasers, with the promise of high power, high-beam quality, good efficiency, and frequency agility offer the promise of defense against high-maneuverability, low-flying supersonic missiles. This chapter summarizes a range of potential laser mission areas and capabilities.

Laser Approaches

There are four fundamental approaches to high- and medium-power laser energy: chemical lasers, solid-state lasers, fiber lasers, and free-electron lasers.

Chemical Lasers

Chemical lasers can achieve continuous wave output with power reaching to multi-megawatt levels. Examples of chemical lasers include the chemical oxygen iodine laser (COIL), the hydrogen fluoride (HF) laser, and the deuterium fluoride (DF) laser. There is also a DF-CO_2 (deuterium fluoride-carbon dioxide) laser.

The COIL laser is fed with gaseous chlorine, molecular iodine, and an aqueous mixture of hydrogen peroxide and potassium hydroxide. The laser operates at relatively low gas pressures, but the gas flow has to be nearing the speed of sound at the reaction time. The low pressure and fast flow facilitate the removal of heat from the lasing medium in comparison with high-power solid-state lasers. The reaction products are potassium salt, water, and oxygen. Traces of chlorine and iodine are removed from the exhaust gases by a halogen scrubber.

The COIL laser was developed by the U.S. Air Force in 1977. The Airborne Laser (ABL) and the Advanced Tactical Laser (ATL) systems both use chemical oxygen iodine lasers. In 2005 the ABL COIL achieved a major milestone, i.e., the complete 6-module laser system was run reliably at power levels and durations necessary for achieving lethal effects. The ATL COIL concept, which involves a sealed exhaust system, was demonstrated in ground tests

Solid State Lasers

Diode-pumped solid-state (DPSS) lasers operate by pumping a solid gain medium (for example, a ruby or a neodymium-doped YAG crystal) with a laser diode.

The most common DPSS laser in use is the 532 nm wavelength green laser pointer. A powerful (>200 milliwatt) 808 nm wavelength infrared laser diode pumps a neodymium doped yttrium orthvanadate (Nd:YVO4) crystal that produces 1064 nm wavelength light. This is then frequency-doubled using a nonlinear optical process producing 532 nm light. DPSS lasers have advantages in compactness and efficiency over other types.

High-power lasers use many laser diodes, arranged in strips. This diode grid can be imaged onto the crystal by means of a lens. Higher brightness (leading to better beam profile and longer diode lifetime) is achieved by optically removing the dark areas between the diodes, which are needed for cooling and delivering the current.

The beams from multiple diodes can also be combined by coupling each diode into an optical fiber, which is placed precisely over the diode (but behind the micro-lens). At the other end of the fiber bundle, the fibers are fused together to form a uniform, gap-less, round profile on the crystal. This also permits the use of a remote power supply.

A current major objective of the Joint High Power Solid State Laser (JHPSSL) program is to produce a 100 kW solid-state laser.

Slab lasers are one class of high-power solid-state bulk lasers, where the gain medium (laser crystal) has the form of a slab.

Fiber Lasers

Combining the outputs of many fiber lasers (100 to 10,000) is a possible way to achieve a highly efficient HEL. Fiber-laser technology continues to advance. At 1 μm, 200 W amplifiers are available commercially, and > 500 W has been demonstrated in the lab. At 1.55 μm, which may be required in applications where eye safety is a concern, 80 W amplifiers are available commercially, and 180 W has been demonstrated in the lab. Various beam-combining experiments have been done.

Free-Electron Lasers

Free-electron lasers (FELs) are unique lasers in that they do not use bound molecular or atomic states for the lasing medium. FELs use a relativistic electron beam (e-beam) as the lasing medium. Generating the e-beam energy requires the creation of an e-beam (typically in a vacuum) and an e-beam accelerator. This accelerated e-beam is then injected into a periodic, transverse magnetic field (undulator). By synchronizing the e-beam/electromagnetic field wavelengths, an amplified electromagnetic output wave is created. Adjusting either the e-beam energy or the transverse magnetic field allows for the wavelength to be tuned. FELs thus have the widest frequency/wavelength range of any laser type.

Free-electron lasers are expected to produce power levels in the multi-megawatt class. The Navy is pursuing FELs for integration on a future all-electric ship to provide ship defense. In 2006 Jefferson

Laboratory achieved a new record average power from free-electron laser: 14.3 kW at 1.6 μm (a good wavelength for maritime propagation).

HEL Science and Technology and R&D Funding, Fiscal Year 2007

DOD funding for high-energy research and development (R&D) in fiscal year 2007 totals $961 million, as shown in Table 1. About 70 percent of this investment is for major projects, principally the ABL program ($629 million). The core S&T investment is about $218 million. This core investment is diffuse, spread across six DOD organizations: the military departments, the Defense Advanced Research Projects Agency (DARPA), the Missile Defense Agency, and the High Energy Laser–Joint Technology Office (HEL-JTO). Funding for these six organizations ranges from a low of $6 million for the Navy to a high of $71 million for the Air Force. The diffuse nature of the funding is somewhat mitigated in the solid-state laser area, in which the Army, Air Force, and the HEL-JTO have combined to fund the JHPSSL. Some highlights of S&T advances and accomplishments over the past few years include:

- **Solid-State Lasers**. A major focus of the HEL technology community has been to increase the average power of solid-state lasers. The HEL-JTO, the Army, and the Air Force have been funding the JHPSSL program, with the goal of producing a 100 kW solid-state laser. DARPA has been funding the High-Energy Liquid-Laser Area Defense System with a similar goal. Under the JHPSSL program, a 1.06 μm Nd:YAG laser has been developed and demonstrated with the following characteristics: 19 kW average power, beam quality of 1.7, and a run time of > 5 minutes.

  A significant materials development affecting solid-state lasers has been the introduction of Nd:YAG ceramics. Replacing crystalline material with ceramics has the potential to considerably improve the manufacturability of solid-state lasers.

Table 1. Funding for DOD High-Energy Laser Programs in FY2007

DoD Organization	Program Element	PE Title	Project #	Project Title	$K
Army	62120A	Sensors & Electronic Survivability	A140	HPM Technology/ SSL	1,652
Army	62307A	Advanced Weapons Technology	42	HEL Technology	18,618
Army	63004A		L96	HEL Technology	9,056
Navy	62114N	Power Projection	None	Directed Energy	6,422
Navy	63114N	Power Projection	None*	Lasers	2,600
Navy	63925N	NAVSEA	None*	FEL	3,500
Navy			None*		19,500
Air Force	62605F	Directed Energy Technology	4866	Lasers & Imaging Technology	23,324
Air Force	62605F	Directed Energy Technology	4866*	Lasers & Imaging Technology	1,800
Air Force	62605F	Directed Energy Technology	55SP		9,471
Air Force	63605F	Advanced Weapons Technology	11SP		9,368
Air Force	63605F	Advanced Weapons Technology	3151	High Power Solid-State Laser	17,350
Air Force	63605F	Advanced Weapons Technology	3151*	High Power Solid-State Laser	9,300
Air Force	63605F	Advanced Weapons Technology	3647*	HEL Technology	3,915
DARPA	62702E	Tactical Technology	TT-06	Advanced Tactical Technology	42,695

Table 1 (cont). Funding for DOD High-Energy Laser Programs in FY2007

DoD Organization	Program Element	PE Title	Project #	Project Title	$M
MDA	63175C			Laser Technology	15,000
AF-JTO	61108F		5097	HEL Research Initiatives	12,356
AF-JTO	62890F		5096	HEL Research	48,936
AF-JTO	62890F		5096*	HEL Research	3,200
AF-JTO	63924F		5095	HEL Advanced Technology	3,699
JNLWD	62651M	JNLW Applied Research		NL Fiber Laser	$0.33
JNLWD	62651M	JNLW Applied Research		Laser Obscurant Interaction with Windshields	$0.18
				S&T Total	261,762
*Of the S&T total $43.8M is Congressionally directed.					
MDA	603883C	BA4	810	ABL Block 2006	595,427
MDA	603883C	BA4	602	Program-wide Support	33,531
SOCOM	116402BB	BA3	S200	ATL ACTD	45,000
JNLWD	63851M		ATL		0.00
JNLWD	63851M			PEP	0.30
				Major Project Total	673,958
Army	605605A	DoD HELSTF	E97	HELSTF	16,438
OSD	63941D	T&E S&T	T&E5	DE	8,828
				T&E Total	25,266
				Grand Total	960,990

- **Beam Control.** The most significant activity in advanced beam control was in the relay mirror area. In 2006 the contractor and the Air Force Research Laboratory (AFRL) used a subscale relay mirror system in a significant ground-based demonstration. The relay mirror was hung on a crane, and a low-power laser was relayed from a ground station two miles away and onto a target. The ABL beam-control system is currently being flight tested. Completion of these tests will be a major milestone for the ABL, but in terms of advanced technology, this system was largely designed over a decade ago.

Applications

Table 2 provides a summary of some identified capability gaps where laser applications might prove to be a viable solution. The figure also includes some performance parameters appropriate to the application. The listing is not exhaustive but is intended to provide a sense of the breadth of possibilities.

Low- and Medium-Power Applications

Advances in electrically based solid-state and fiber lasers have made useful low-power applications achievable within a few years. These include less-than-lethal applications at power levels ranging from less than a watt to 10s of watts of average power. Low-power lasers can provide the capability to “dazzle” snipers and the operators of small surface ship threats (jet skis, small boats), and to counter visible and infrared sensors and night vision systems. Active sensing could have application to remote detection of weapons of mass destruction, IEDs, floating mines, and imaging, in support of high-altitude airborne precision strikes.

Systems with improved efficiency and reasonable beam quality for solid-state and fiber lasers offer the promise of manned and unmanned aircraft applications at power levels of hundreds of kilowatts for self-defense and precision ground attack at distances to 10 kilometers with moderate beam control system apertures (5-30 cm).

Table 2. Representative Laser Mission Areas and Capabilities

Mission Gap	Range	Required Technologies/Device Power	Status Maturity/Availability	Cost
Aircraft Self-Protection	<10 km	Diode Pumped SS Osc with Freq. Conversion	TRL 9, 400 Built	1.5-3M per aircraft
Ground-based Counter-Sniper	100m-2 km	Warn/Dazzle:1-100W Strike 5kw SSL with 20-30m aperture	Warn/Dazzle handheld TRL9 Long range TRL4	<$100M to develop $1M/copy
Low-Altitude Airborne Counter-Sniper	3-5 km	Warn/Dazzle: 100W Strike: 10-15kw SSL with 20-30 cm aperture	Fieldable prototype in 2 yrs	$100M to develop $10-$20M/ copy
Ship Surface Threat Defense	1-2km	Warn/Dazzle: 10s-100s W Strike: 10s of KW SSL with 20-30 cm aperture	Warn/Dazzle: prototype in 1 yr Strike: prototype in 2 yrs	$10M to develop $Ms/copy
Robust Aircraft Self-Protection	5-20km	50-100W		
High-Latitude Airborne Strike	Imaging: 20+km Strike: 10km	Imaging: 100W with 30cm aperture Strike: 50-100kw SSL w/ 30 cm aperture	Imaging: TRL 5/6, 2 yrs to field Strike: TRL 3/4	
Ground-based/Air & Missile Defense, Counter-RAM	5-10km	100s of KW CL w/ 1m aperture 100s of KW SSL w/ 30-50 cm aperture	CL TRL 6 , field in 18 mos. SSL TRL4 demo in 4-5 yrs	CL $200M prototype, %$50M/copy SSL: $200M to demo, $500M to prototype
Ballistic Missile Boost Phase	100s of km	MW-class chemical laser	Shootdown demo in 2009	
Battle Group Defense	5-20KM	1-3 MW Free Electron Laser	TRL 2, prototype in 2020	

Dazzler/Optical Augmentation Systems

Examples of dazzler/optical augmentation systems (1-100w visible lasers) include the P208 rifle-mounted dazzler for sniper detection at <2km, detections and unambiguous warning sensor for ship protection at <2km, and CSAR-X/ACCM large area dazzler for para-rescue helicopters.

Laser-based optical incapacitation devices have been deployed to Iraq in response to urgent fielding requirements for a non-lethal means to warn or temporarily incapacitate individuals. Marines employing these devices have reported that "they consistently defuse potential escalation of force incidents." Laser devices currently employed by the Marine Corps are green laser (532 nm) systems emitting a strong beam that can temporarily reduce visual acuity at a distance of 300m or more. It has a nominal ocular hazard minimum distance that the operator must avoid to preclude risk of eye injury. The lasers have been successfully used in convoy operations, mounted and dismounted patrols, vehicle check points, and entry control points. Army units have also purchased laser optical incapacitation devices of various types, principally for use in escalation of force situations and to warn or deter drivers of cars approaching checkpoints, U.S. convoys, or fixed-site installations.

Issues. The use of lasers to temporarily incapacitate personnel is new for DOD, especially lasers that if inadvertently used inside of their minimum safe range may cause irreversible eye damage. Laser optical incapacitation devices are being procured only on a case-by-case basis to support urgent operational requirements. For example, the Marine Corps received approval to use the green laser in theater from the Navy Laser Safety Review Board for a limited period of time (March 2008). There is no existing program of record for sustaining or improving the capability.

Aircraft Self-Protection

Low-power solid-state devices can provide countermeasures against infrared-based threats <10 km. Examples include the Guardian DIRCM, with both ultra-violet and two-color infrared missile warning sensors, and a Viper solid-state, laser-based jammer.

Aircraft self-protection is an urgently needed capability. Medium-power solid-state lasers or beam-combined fiber lasers, along with appropriate beam-control systems (e.g., an electrically steerable beam director conformable to the aircraft surface), could potentially address this need.

Ground Attack

Similar laser systems enable precision ground attack to minimize collateral damage in urban conflicts and in close proximity to friendly troops. Future gunships could provide extended precision lethality and sensing. High-altitude airborne precision strikes, enabled by solid-state or fiber systems with hundreds of kilowatts, aperture sizes of 10s of centimeters, and the use of adaptive optics for atmospheric compensation, offer enhanced air platform survivability.

UAV Defeat

Ground-based electrical laser systems used with mobile weapons platforms could provide the ability to defeat the rapidly growing threat of unmanned aerial vehicles (UAV) as sensor platforms and weapons carriers. Medium-power lasers are effective in this near-term application because of the relative vulnerability of UAV platforms and the rapid expansion of UAVs on the battlefield.

Defense Against Rockets, Artillery, and Mortars (RAM)

Extended air defense is another critical application to protect against RAM and missiles. The promise of medium-energy lasers to quickly engage and defeat such systems has been demonstrated in preliminary field tests.

High-Power Applications

Chemical lasers in a variety of forms (COIL, HF, and DF lasers) have provided test beds for critically needed lethality and beam control experiments, and have served as the first generation of high power systems for aircraft integration. The ABL, based on a megawatt-class, COIL-integrated laser weapon demonstration system on a 747-400 platform, is to provide a first generation ballistic missile defense capability, while demonstrating that chemical lasers offer airborne systems for a variety of applications.

Advances in electrical laser power, quality, and efficiency have made solid-state and fiber lasers the preferred next-generation systems of choice.

Airborne Laser

The Airborne Laser was conceived in the early 1980s and has evolved from a laboratory initiative (Airborne Laser Lab) to demonstrate the feasibility of operating an aircraft-based CO_2 laser with both pointing and tracking and weapon system capabilities.

The current focus of the ABL program is to demonstrate missile shoot-down capability with a prototype laser weapon system. Efforts in the past years have been focused on integrating a multi-megawatt COIL with a 1.3 micron wavelength into a modified Boeing 747, along with an adjunct laser pointing and tracking system to provide acquisition, detection, and target tracking. Figure 1 shows the components of the weapon system as integrated on the 747.

During operation, the aircraft will cruise at altitudes approaching 40,000 feet and use onboard infrared sensors to provide autonomous detection of missile boost phase plumes. The Ballistic Missile Defense System (BMDS) also provides detection and target handover data to ABL and integrates the weapon system into the global BMDS (a tiered system consisting of ground-, sea-, and space-based elements) through communication links in development. Similarly, the ABL is to provide detection and pointing and tracking information to BMDS. Depending upon the construct of the BMDS detection, discrimination, and designation system, the ABL could potentially provide data for discrimination.

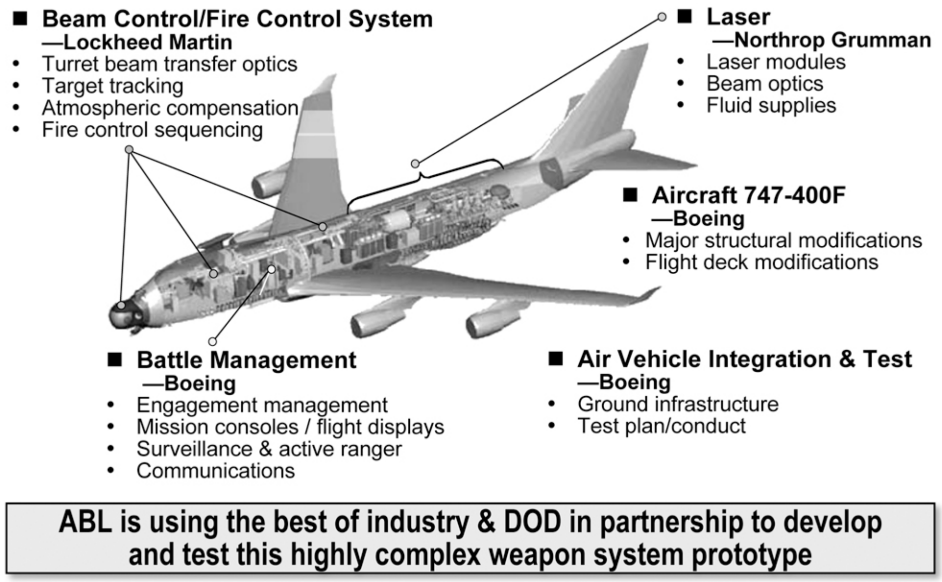

Figure 1. Airborne Laser Weapon System Elements

Issues. Turning a laser system into an effective weapon proved to be more difficult than projected at the time of the 2001 DSB review, as the ABL was scheduled to demonstrate a lethal intercept in 2003. However, the ABL did not have a separate technology base to build upon. As the program progressed, each of the subsystems that comprise ABL required extensive development, along with establishing functional interfaces with other subsystems and integrating into the airborne platform environment. Examples of ABL technology development include increasing the specific power (watts/lb) of the COIL, enhancing beam control to increase the fluence (watts/cm2) on the target, and improving atmospheric compensation techniques.

Since the time of the previous DSB review, the program has been transitioned into the Missile Defense Agency (MDA) and several key objectives have been met, as shown in Figure 2, in the progression to an integrated weapon system. Passive flight tests of the beam control system, as well as long duration tests (72 lasers with a total duration of 82 seconds) of the COIL in the ground test environment. In addition, both the beacon illuminator laser and the track illuminator laser have been ground-tested. MDA established specific “knowledge points” to highlight the developments essential on the acquisition path to integrating and demonstrating a prototype weapon system.

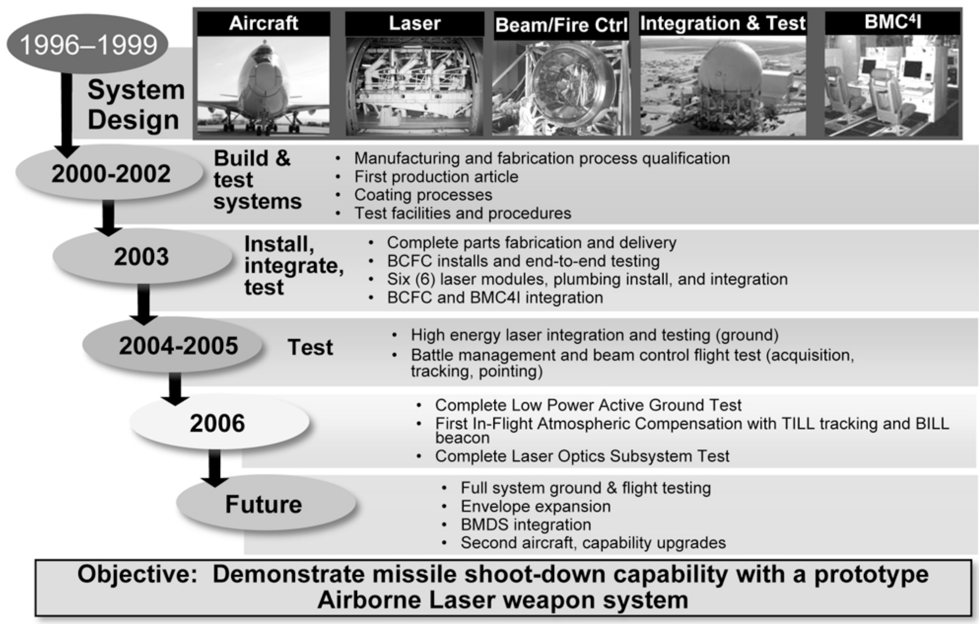

Figure 2. ABL Program Progression

Schedule and Funding The ABL program is to complete laser installation in the 747, conduct a ground test of the ABL weapon system, demonstrate the airworthiness of the ABL, and demonstrate a lethal intercept by late 2009.

Funding for the current program (T-1) has been based upon a single aircraft being used for the ABL development, apart from aircraft used for tracking and targeting purposes. Upon completion of the 2009 lethal demonstration, a decision could be made to move to more advanced laser technology, such as electrically powered solid-state lasers when they become available, though the technology for the needed power levels is not on the near horizon.

Tactical High Energy Laser

Program Description. At the time of the 2001 DSB review, the Tactical High-Energy Laser (THEL) represented the low-risk, low-cost approach to field a high-energy laser system with operational capability of value in defending against air and missile attacks on forces, urban areas, or critical infrastructure. The DF laser demonstrated, in tests, effectiveness in destroying Katyusha rockets and airborne targets, including simultaneous engagements of both airborne and rocket-launched targets. THEL was the first laser weapon system developed by the United States.

Interest from an allied government hastened the development of a "mobile" (actually relocatable) THEL (MTHEL)by focusing on implementing a more compact and transportable operational version of the 3.8 micron wavelength DF laser. Evolving requirements from the customer, concerns about the logistics tail in fielding, and operating a relocatable system in a battlefield environment that employs toxic and corrosive chemicals caused the program to be terminated.

Mobile Directed Energy Weapons System

Program Description. The termination of the THEL/MTHEL programs served as a significant turning point in the Army's laser development. Employing toxic and corrosive systems in a battlefield environment that could operate with certainty in all weather conditions was a price that warfighters, even with a need for enhanced defensive system effectiveness, were unwilling to pay. This caused a reevaluation of the program's path as compared to what had been projected at the time of the 2001 DSB assessment.

Building upon the knowledge gained from THEL/MTHEL (to include acquisition and track, aim point selection, beam control, kill assessment, as well as concepts of operations, logistics, and supportability), the Army embarked on a broader-based S&T program. The Space and Missile Development Center, Army Research Laboratory, Army Air Defense Artillery School, and the DOD High Energy Laser Joint Technology Office share the responsibility for identifying needs and developing the elements and components essential for future ground-based high-energy laser systems. Goals for the projects include exploring land-based directed energy weapon solutions for mine clearing, responsive precision fire support (both line-of-sight and near line-of-sight), counter rockets, artillery and mortars, air defense (i.e., an element of the Extended Area Air Defense System), and, eventually, space control.

The program strategy adopted post-THEL/MTHEL is to demonstrate high-power solid-state laser technologies, adopt the laboratory solid-state lasers for ground-based systems, conduct military utility assessments, and then weaponize the elements and subsystems for the Army's needs following propagation and lethality testing. Based upon prototype system-level demonstrations, decisions to proceed with weapon system development programs can then be made relying upon a technical foundation necessary for schedule, budget, and implementation planning. Thus, what exists today is a collection of S&T projects intended to lead to a program of record.

Issues. First order challenges facing tactical ground-based laser system development are shown in Figure 3. The Army has chosen to address the system development risks by breaking the weapon system down into its essential elements and concentrate on each element as follows:

- The JHPSSL program, led by the Army's Space and Missile Development Center, is to develop a 100+Kw optical output power device. Beam quality relative to the diffractive limit is projected to be "excellent;" that is, less than 2xDL, with a goal of <1.5xDL. (1xDL is perfect beam control.)
- In parallel, the HEL technology demonstrator is projected to develop beam control system(s) that will be ready for pointing and tracking, as well as subsystem level range tests after JHPSSL delivers a laboratory solid state laser device.
- The option exists, depending upon system level assessments of target lethality, modeling, and simulation of notional system level concepts, and the success of the JHPSSL and the beam control system technology developments, to integrate the elements into a mobile demonstrator (a possible component of Future Combat System) for proof of concept tests beginning in fiscal year 2012.

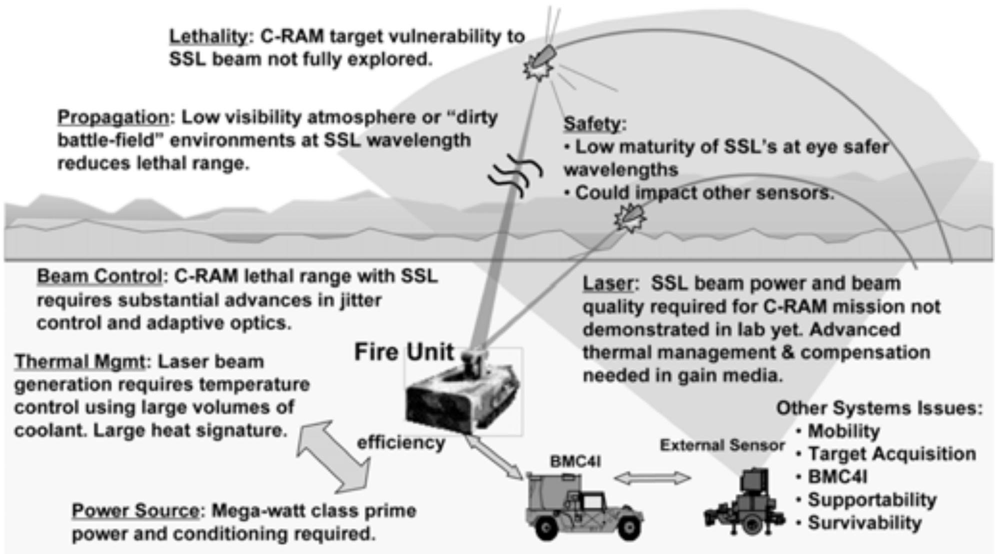

Figure 3. Solid State Laser Weapon System Critical Issues

There are important issues to address in this "program of projects" spread across several organizations. Issues include determining how much laser energy is essential to provide the desired effects for each system application, developing tailored system designs based upon available technology for credible force implementation, ensuring the various laboratory elements of a weapon system are sufficiently rugged, and demonstrating the operability of developed weapon systems.

Eventually, the solid-state laser design concept selected may operate at ~400 kW for several minutes, but today's current laboratory demonstration of 15-40 kW for a few seconds indicates that technology advancements in the collection of Army projects are critical for eventual weapon systems applications. For ground-based systems, all weather operation would appear to represent a continuing limitation.

Schedule and Funding. Funding appears to at the level of approximately $50 million a year each from the Army and the Joint Technology Office for projects that would support ground-based HEL initiatives. Future system progress is strongly driven by progress in this area. Both lethality initiatives and modeling and simulation development for systems, elements, and components (that also relies upon lethality for end-to-end performance assessment) appear disconnected and underfunded.

Advanced Tactical Laser

Program Description. Since the 2001 DSB review, the ATL advanced concept development program has evolved to a program objective to build and conduct a military utility demonstration of a modular, high-energy, closed-cycle laser weapon system on a C-130 aircraft. Day/night operational capability and adjustable laser dwell times are to be demonstrated over Air Force Special Operations Command-specified mission scenarios. Targeting objectives (such as disable aircraft on ground, create roadblock, clear building, close air support, and limited conflict strike) must be accomplished covertly (without thermal signatures) from varying altitudes, but typically close range, as opposed to the high-altitude, long-range, significantly higher-powered ABL weapon system.

U.S. Special Operations Command serves as the executing agent through U.S. Army Space and Missile Development Center and the Air Force Research Laboratory. Air Force Special Operations Command is the operational manager.

The configuration of the ACTD is shown in Figure 4. In some regards the ACTD is analogous to the Airborne Laser Lab (the predecessor of ABL) in that the objective is to focus on the laser and subsystem technology developments, rather than spending resources to shrink-fit the lab-developed packages into an airframe; e.g., plans in 2001 to use the V-22 or Ch-47 as the ACTD platform have been abandoned in favor of the larger volume, heavier payload capability C-130. The laser, optical control subsystems, and the weapon system management station are developed independently before integration on the modified C-130H.

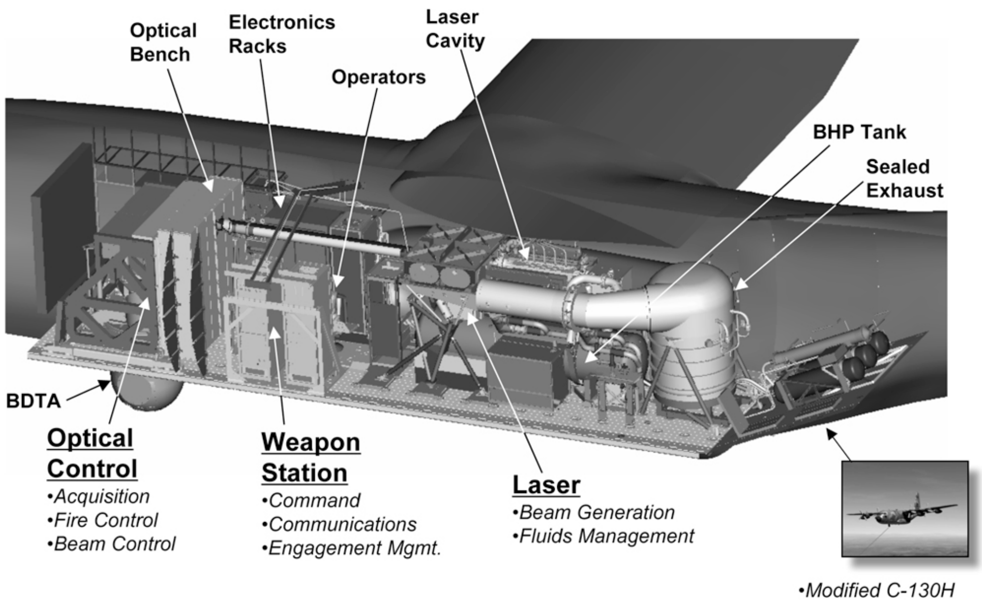

Figure 4. High Power A/C Configuration

Issues. The ACTD is relying upon success in parallel technology development projects, many of which represent significant challenges. While an ATL could offer military utility with the COIL system that has been under development, the direct exhaust system will not work well at the lower altitudes typical of Special Forces operations.

The alternative closed-cycle system (CC-COIL) also has some inherent weaknesses. For example, magazine capability is limited by the sealed-exhaust system size. Further, chemical lasers, despite the recirculation and regeneration developments, retain logistics liabilities. In addition, the ability to obtain significant increases in power with the system architecture has been elusive for future long-range operations. The rudimentary beam control system currently implemented does not support the precision and range potential of the system.

Schedule and Funding. Development accomplished to date on the ACTD and progress achieved has positioned the CC-COIL to be ready for a decision to proceed in utility evaluations projected in 2009 and 2010, as described in Figure 5.

ATL funding for fiscal year 2007 was $45 million. This is the final year of the ACTD. The Air Force has picked up the extended user evaluation beginning in the second quarter of fiscal year 2008 for further exploration of the ATL mission set and preservation of the test program.

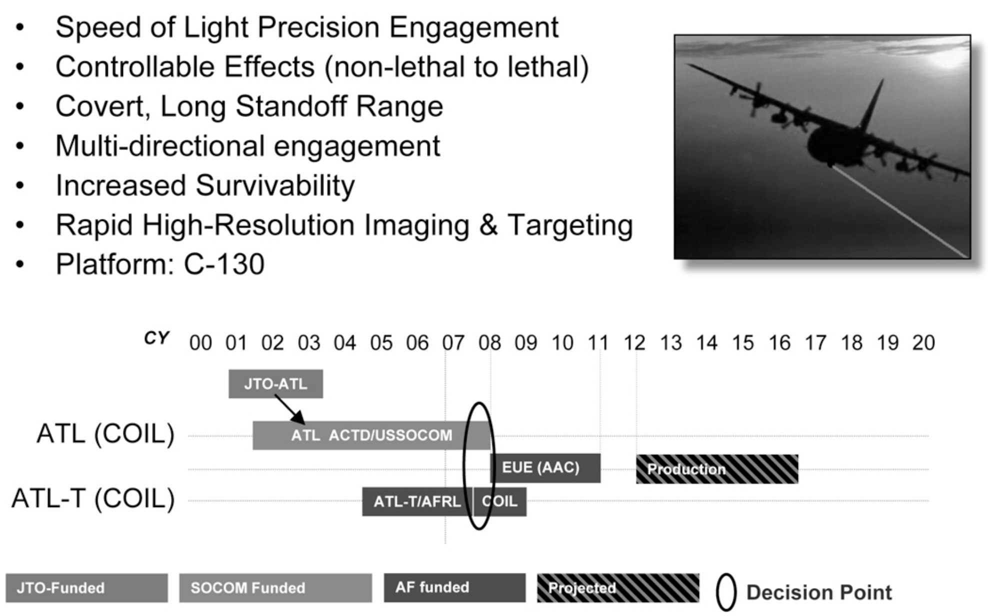

Figure 5. ATL Parallel Technology Development Program

Maritime Self-Defense

As noted earlier, the Navy has a need for an effective high-energy laser system for defending high-value ships against supersonic missiles. Existing stressing threats are represented by a new anti-ship missile with a rocket-propelled warhead that has the ability for high-g defensive maneuvers as it approaches its target. Particular characteristics make the warhead a particularly difficult system to counter with kinetic energy weapons.

The free-electron laser, with its favorable scaling to high power, beam quality, ability to be tuned for enhanced maritime propagation, and efficiency make it an attractive candidate for ship defense against such threats. Used in combination with kinetic energy systems, the "deep magazine" of the FEL enhances the utility of both systems. The ability of large-aperture beam directors for high-precision locating and tracking also supplements the capability of Aegis-radar-based acquisition and tracking systems, offering more time for the combined directed energy-kinetic energy defensive system to engage this stressing threat.

Program Description. The breadth of the options being explored for maritime applications is illustrated in Figure 6. FEL can be scaled to higher powers through continued evolutionary upgrade of the beam source. In addition, the FEL can operate at selected or tunable wavelengths depending upon the laser configuration, and it offers good beam quality. Although eventually the FEL could provide an effective and affordable point defense capability against current surface and air threats, as well as potential anti-ship cruise missiles, near-term efforts are focused on countering asymmetric threats and swarms of small boats, and providing surveillance and inspection to prevent direct entry from the sea to U.S. ports by nuclear terrorists on dedicated ships.

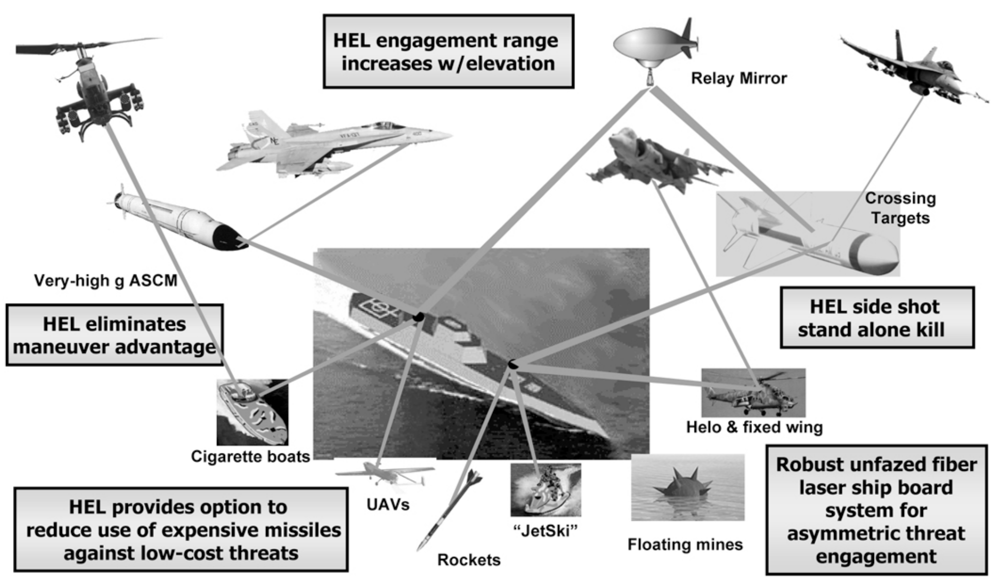

Figure 6. Directed Energy Weapons for Force Protection and Self Defense

The approach advocated by Naval Sea Systems Command is to build upon the efforts conducted in the Army, the HEL-JTO, and the Office of Force Transformation so that an initial (Block 1) capability can be demonstrated with a 50-100kw fiber laser with inherent modest beam quality against RAM, UAVs, floating mines, and asymmetric threats (such as jet skis and cigarette boats) within a kilometer of the platform. In addition, the system could damage electro-optical sensors as well as negate the effectiveness of close-range, man-portable artillery devices.

A higher power laser in Block 2 with improved beam quality could provide increased standoff ranges. Injection of the FEL in Block 3 would offer initial laser theater ballistic missile defense capability for the surface Navy that could be integrated into current concepts of operation. Future upgrades (Block 4) achieved with >1Mw FEL and relay mirrors could offer the potential for littoral offensive support as well as fleet defense against more robust airborne attack platforms.

Issues. This program is a collection of multi-agency projects that depend upon appropriate funding and technology development in each to achieve the vision. Maritime defense using lasers has been studied since the late 1960s and assessed in various laboratory-level investigations, but results to date have not brought the system to fruition. The rationale for FEL development appears solid, but it is apparently not the top priority of a very broad set of technology projects spread across several agencies.

Other technology development efforts; such as laser beam control technology, as shown in Figure 7, and ultra-short pulsed lasers, described in Figure 8, are, or could be, common to Army, Air Force, or MDA pursuits and, thus, have an inherently broader base of support for wringing out issues. But the top technology risk for the Navy is the transition of a FEL from a low-power laboratory development to a high-power weapon system that can be used at sea.

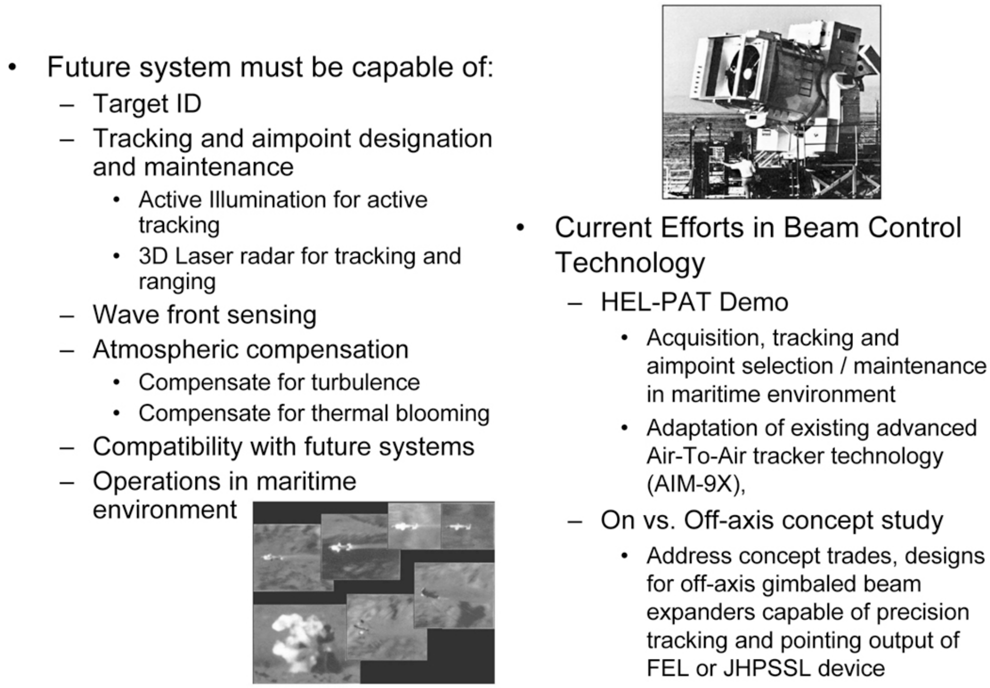

Figure 7. Laser Beam Control Technology

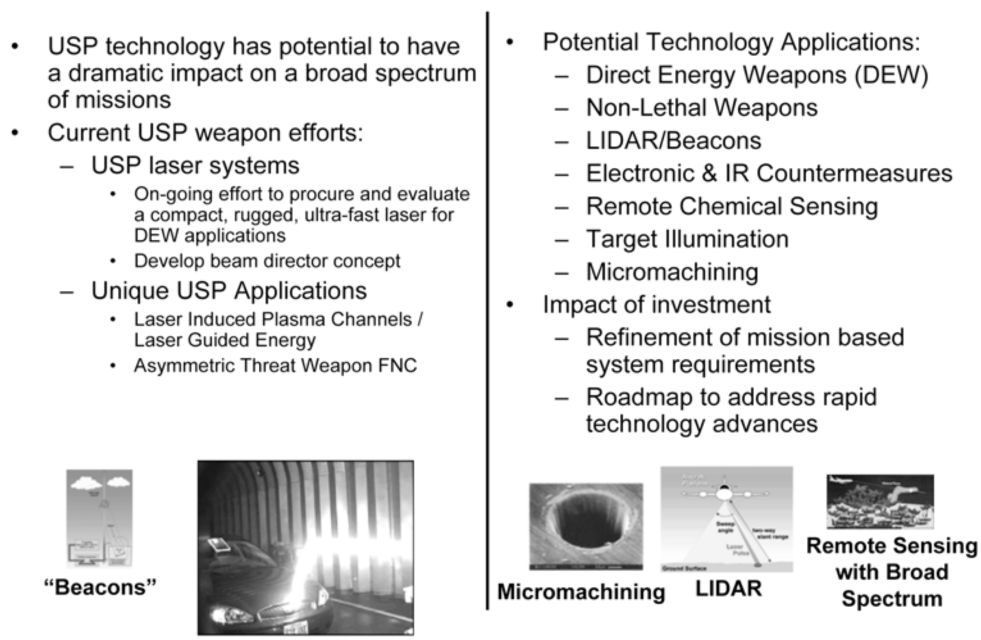

Figure 8. Ultra Short Pulse Laser

Funding and Schedule. The Navy programs are funded at about $10–15 million per year in the current future years defense plan. The Office of Naval Research vision of FEL availability for implementation in 2025 is shown in Figure 9.

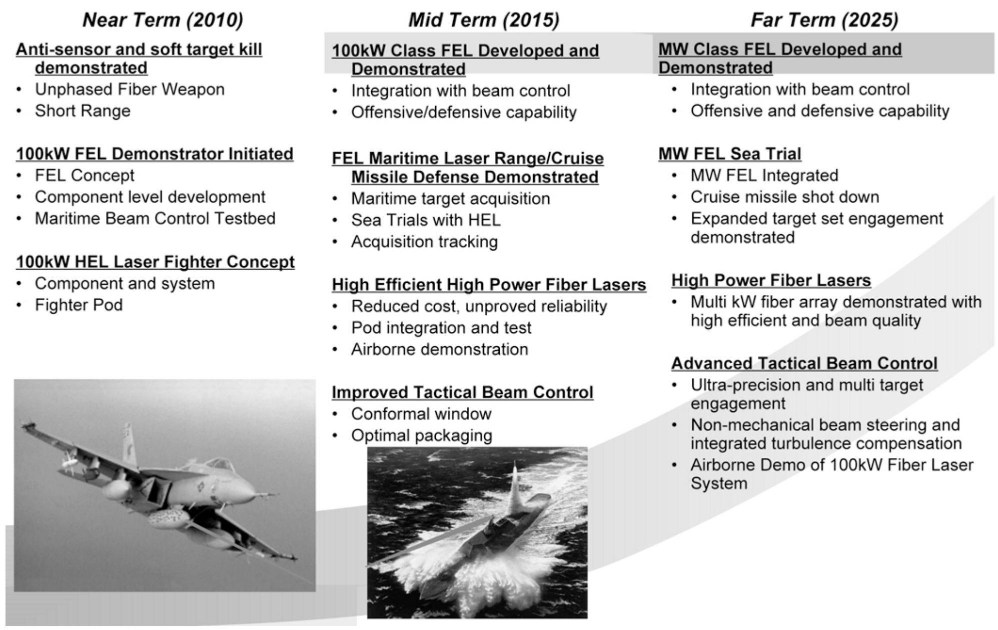

Figure 9. ONR Directed Energy Vision

System Enabling Developments

The Office of Force Transformation has sponsored a suite of enabling technologies that could speed the utility of directed energy weapons in the battlefield. Figure 10 shows the possible evolution of these concepts. Initially, in two to three years, a 25kW HEL could be used with aerostat-based laser relay systems to increase the range of line-of-sight weapon systems dramatically in urban areas. The low power stationary laser could use the legs offered by the relay system to detect and track targets (placement of IED or threats to forward operating bases) and engage (disarm or destroy) the targets. Successful development of the 100kW laser will permit an expansion of capabilities within five years using the aerostat relay system to counter RAM and, potentially, cruise missiles that could threaten ports or ships.

Eventual mobile operation of a ~200kW ground-based HEL, coupled with development of an UAV-based laser relay system, could offer, in the longer term, the potential of both force protection and force projection with precision strike of selected targets.

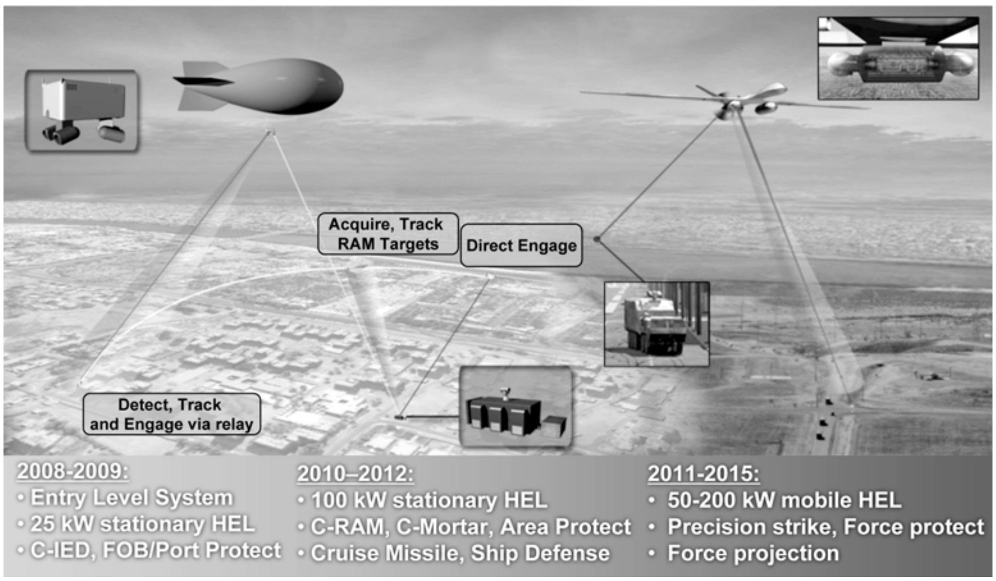

Figure 10. Tactical Laser Relay Systems Will Evolve to Address a Range of Mission Needs

Recent S&T accomplishments, although technically impressive, have often demonstrated performance well short of that required for DOD applications, and have done so in configurations that have not addressed manufacturability, packaging, maintainability, and other similar concerns that are critical for making HELs operationally acceptable. For example, although the JHPSSL and FEL results mentioned above represent significant advances for the particular classes of lasers involved, the power levels of 19 kW and 14 kW, respectively, are approximately two orders of magnitude lower than the megawatt-class outputs already obtainable with chemical lasers. In addition, the JHPSSL lasers and the Jefferson Laboratory FEL are basically laboratory experimental devices; they have not been built to demonstrate the packaging and "ilities" necessary for operational systems. Similarly, in the beam-control area, the relay-mirror system was used in an impressive end-to-end functional demonstration; but the overall pointing accuracy was coarser than required for strategic applications, and the relay-mirror system was constructed from parts and sub-systems that are not traceable to an operational system.

Laser system developments (parallel projects) and payload systems for Predator class UAVs remain pacing items for any eventual HEL relay system evolution.

Laser Systems Effects

The HEL-JTO has formed a working group to address the methodology issues with continuous wave or pulsed lasers effects. The difficulty is establishing the coherent program that has the funding and organizational capabilities to exploit targets (or design meaningful emulators) and test them in a way that vulnerability assessments of subsystems or components can be provided to all HEL developers.

Modeling and simulation of the system (shown, for example, in Figure 11) begins with laser-target interaction (lethality or damage) as identified above and then working backwards to determine what beam control, adaptive optics, and laser device power are necessary to enforce ranges of interest. Without that consistent methodology and database applied uniformly, it is not possible to assess the relative merits of competing notional concepts for directed energy weapon operation with kinetic weapons, or as a replacement for them in certain instances.

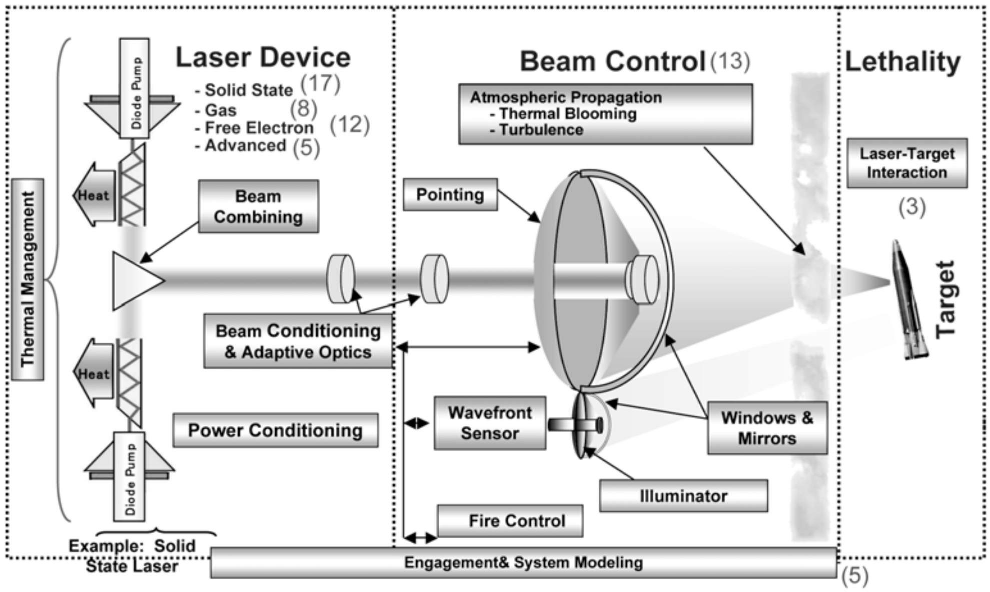

Figure 11. High Energy Laser System Construct

Findings and Recommendations

- There needs to be a rigorous analytical effort to identify those capability gaps for which laser weapons are likely to be the most effective solution.
  - *The Deputy Secretary of Defense should direct that the military departments provide rigorous analyses to determine where capability gaps are best addressed by directed energy weapons and provide roadmaps of the path to developing such capabilities.*
- Enhanced modeling and simulation capabilities for laser systems are needed to reduce development times and costs, and to ensure that operational and logistics considerations are understood and addressed.
  - *USD (AT&L) should direct development of non-proprietary modeling and simulation capabilities to be made available to government and contractors.*

- *There needs to be an authoritative single source database for directed energy effects similar to the munitions effects manual for kinetic weapons.*

- Research and development needs to be concentrated on those applications where rigorous assessment shows that a laser weapon is the preferred solution vice a kinetic weapon.

  - *USD (AT&L), the Director, Program Analysis and Evaluation, and the military departments should establish programs analyzing the cost and benefit of promising applications of laser energy to fill identified weapons needs.*

- S&T funding for laser application is fragmented across a wide range of explorations and activities without established priorities.

  - *USD (AT&L) should task the Director, Defense Research and Engineering (DDR&E), to develop directed energy S&T priorities for FY09 and beyond so that projects and programs that support the identified R&D can be properly supported.*

- S&T funding for laser weapons should be heavily focused on solid-state and fiber lasers with at least 100 kilowatts of power and with significantly improved beam quality and control.

  - *DDR&E should give high priority to S&T activities addressing high power solid state laser development, fiber beam combining, and accompanying beam quality and beam control development.*

- S&T funding for low- and medium-power laser applications should be concentrated on a defined set of applications meeting high priority needs to include defeating UAV platform mission capabilities, defeat of MANPADS, and defeat of rockets, artillery, and mortars.

  - *USD (AT&L) should task the military departments to provide road maps (strategic plans) to move demonstrated technologies to fielded capabilities in accordance with priorities established by combatant commands and force providers.*

- High-powered chemical lasers, as a more mature technology, should be the preferred first generation solution for high-energy fixed or very large platform applications.

- *USD(AT&L), with support from the Air Force, should identify and support future needs other than ABL and Tactical Airborne Laser and should realign funding for high power chemical lasers to a considered balance between technical development and efforts to field operational systems.*

- The fragmented programs associated with developing a free-electron capability for ship defense should be coalesced into a coherent program directed at providing a fielded system.
  - *The Secretary of the Navy should direct transition to an "Innovative Naval Prototype" program to integrate technology programs into a program that has the potential to develop a fleet defense system.*
- Recent S&T accomplishments, although technically impressive, have often demonstrated performance well short of that required for DOD applications, and have done so in configurations that have not addressed manufacturability, packaging, maintainability, and other similar concerns that are critical for making HELs operationally acceptable.
  - *DDR&E should require that S&T work include focus on operational and logistics aspects. The cost/benefit analyses for each projected application should include consideration of operability and sustainment in the battlespace.*
- Enhanced modeling and simulation capabilities for laser systems are needed to reduce development times and costs, and to ensure that operational and logistics considerations are understood and addressed.
  - *USD (AT&L) should direct development of non-proprietary modeling and simulation capabilities to be made available to government and contractors.*
- There needs to be an authoritative single source database for directed energy effects similar to the munitions effects manual for kinetic weapons.
  - *The Deputy Secretary of Defense should assign responsibility to a military department to develop a laser (and HPM) effects manual.*

Chapter 3. High-Powered Microwave Technology and Programs

There are arguments for treating microwave and millimeter wave systems separately and there are differences in physical properties and current application emphasis. However, for simplicity, this report refers to the full spectrum of these technologies as high-power microwave (HPM). HPM weapons vary widely in effectiveness and development as their design characteristics are varied over a number of parameters. For that reason, these weapons are often categorized first by band ratio. Following Nitsch and Sabath, a set of categories are:

- Narrowband/continuous wave (band ratio about 1 percent)
- Narrowband/pulsed (band ratio about 1 percent)
- Wideband (band ratio < 100 percent)
- Ultra wideband (band ratio >100 percent)

Much of the research budget over the last 15 years has been expended on developing narrowband/pulsed sources with a goal of 1GW, 1 kHz PRF, 1kJ per pulse characteristics (MCTL Draft Report, Barker and Shamiloglu). Currently, at the Air Force Research Laboratory, there is an emphasis in development of a gigawatt (GW) class demonstrator for optimization and development of lighter components. Use of such a demonstrator and the development of design tools allow the United States to capitalize on the earlier investment. These sources suffer from limitations of air breakdown in development of weapon systems.

These limitations include a minimum antenna aperture area. Notable recent successful applications have been primarily in the area of narrowband/continuous wave sources. Active denial is one of those systems that use the depth of nerve endings in the skin to choose a center frequency. Certain counter-IED systems also use bandwidths from 1–20 percent to couple energy efficiently in the IED. These types of sources also have potential in application against electronics.

According to a summary of 94 test series evaluated by Nitsch and Sabath, the damage and upset thresholds for narrowband/continuous wave sources are substantially lower than those from the other categories of sources noted above.

Wideband sources that also include electromagnetic pulse-like sources are only recently being developed, although the technology has been around for many years. Combining a fast switch with a resonant structure or oscillator allows the development of small, light, and effective sources that vary considerably in the level of technology required to build a successful source. These types of sources are best developed for transportable sources that can be delivered close to the target.

Ultra-wideband sources have also recently been developed around the impulse-radiating antenna originally developed through AFRL research not focused on HPM. This antenna was combined with a fast switch to produce the JOLT system that has been widely described in the open literature. It has a record-setting figure of merit (E*r) of 5.5 MV. Its effectiveness as a weapon has not been demonstrated. JOLT and systems like it get much of their high peak fields at a distance by the time-domain equivalent of high directivity. That method has the disadvantage of not covering a large target area for each pulse.

Effects

Determining the appropriate lethal parameter mix requires a serious investment—similar to that applied thus far to source development. A much larger investment in system testing; sources capable of transmitting a wide variety of pulse, waveforms, laboratory and computer simulations; and extensive data analysis of the available test data is required. System testing must be sufficient to obtain statistically significant conclusions, not just single-event demonstrations. Results from the university community performed under a series of multi-university research initiatives for microwave effects have not been widely accepted by the services. Although there is increasing emphasis in effects research (testing and the necessary predictive tools that link the weapons effectiveness predictions to tactical simulations) the task is difficult and more resources are needed in that area.

Low-Technology Solutions

HPM weapons have been built and demonstrated to be effective against commercial electronics, such as systems that control the infrastructure. Components needed to produce such weapons are widely available. Low-cost hardening technology that will appeal to the commercial sector is still needed since many defense systems depend on commercial products.

Transportability

Many of the sources described above have been developed to operate in a laboratory environment. That means they are heavy and require large amounts of prime power. To be useful in tactical applications, lighter, more efficient systems are needed and are under development. Hand-carried, briefcase-sized, truck-mounted, and airborne systems have all been considered and demonstrated. Full system development should be considered for some of these approaches.

Specific Research to Support Effective Use of HPM Technology

Development of more effective counter-IED and counter-mine applications. Investment in this area to date has produced limited results for only a few systems. HPM techniques have been shown to work in specific field applications. That success should act as a baseline to develop more effective, more general, and more easily transportable systems.

Development of an effective airborne platform-mounted system that can stop enemy electronic systems sufficiently long to conduct other attacks and/or surveillance. The decay with distance of HPM field strengths demands that this system must get within about 10 meters of the target limiting effectiveness in many relevant situations. UAVs could be used but have limited surface area bounding the antenna aperture. The consequent antenna directivity allows reasonable ground coverage areas at frequencies of 1GHz or less. Digital buses and the like operate at 10s of MHz, unlike the individual processors that have on-chip oscillators of several GHz and rising. Electronic systems tend to be more susceptible near their operating frequencies. These simple constraints can be used to scope a system that can be effective. Obviously, it must be tested and optimized within the weight, balance, and prime power constraints of a mobile platform.

Simple systems. Many foreign countries have invested in small, technologically simple HPM sources. Diehl of Germany sells several of these sources commercially. These types of sources range from briefcase-sized to truck-mounted. Surplus radar tubes are used and have been shown effective against a variety of electronic systems that are critical to our military and civilian infrastructure.

Effects data. Numerous organizations have attempted to create HPM effects databases that can be used as a "universal HPM effects predictor." All of those efforts have failed to produce a true predictive capability for reasons varying from seemingly slight differences in experimental conditions to the inability to share data between organizations. A better approach is to establish canonical test simulation facilities like the MOATS facility at Dahlgren. This facility represents a complex PC-based headquarters with communications, industrial digital control systems, alarms, and the like in representative buildings. Other canonical systems represent IADS, satellite- and ground-based communications and data processing facilities, and other general use facilities. Sources spanning a large parameter space are required. The British Orion system is an example of such a system. Others could include electromagnetic pulse simulators with fast rising waveforms and simultaneous current injection.

HPM Science and Technology and Research and Development Funding

Table 3 shows the DOD funding for high-power microwave research and development in fiscal year 2007. The funding is spread across the military departments and the Joint Non-Lethal Weapons Directorate (JNLWL). The JNLWL directorate pursues a wide range of kinetic weapons, as well as directed energy weapons. At present, within the JWLWL program, one HPM program is in ACTD status. The rest are in the S&T category.

Table 3: Funding for DOD High-Power Microwave Programs in FY 2007

DOD Organization	Program Element	PE Title	Project Number	Project Title	Dollars (in Millions)
Army	62120A	Sensors & Electronic Survivability	A140	HPM Technology	$972.00
Army	62624A	HPM-NL	H18		$3,030.00
Army	62624A	HPM-NL	H19		$2,789.00
Army	63004A		232		$0.00
Navy	62xxxN	NRL			$330.00
Navy	62114N	Power Projection			$6,000.00
Navy	62114N	Power Projection		HPM Technology	$1,000.00
Air Force	62605F	DE Technology	4867	RF Modeling	$15,424.00
Air Force	62605F	Advanced Weapons Technology	3152	Advanced Weapons & Survivability	$12,890.00
JNLWD	62651M	JNLW Applied Research		RF Vessel Stopping	$0.65
JNLWD	63651M	JNLW Technology Development		RF Vehicle Stopping	$0.50
JNLWD	63651M	JNLW Technology Development		Compact ADT	$0.84
JNLWD	62651M	JNLW Applied Research		Laser ADT	$0.15
JNLWD	62651M	JNLW Applied Research		RF Vessel Stopper Wideband Evaluation	$0.42
JNLWD	62651M	JNLW Applied Research		RF Vehicle Stopper Wideband Evaluation	$0.18
JNLWD	63851M	JNLW Demonstration / Validation		ADS ACTD	$4,500.00
				Total	$46,937.74

HPM Applications

Active Denial System

Program Description. The Active Denial System (ADS) ACTD is a non-lethal, counter-personnel, line-of-sight directed energy weapon, using a controllable millimeter-wave beam to produce an irresistible heating sensation on the adversary's skin causing an immediate deterrence effect. Operational applications include area denial, force protection, maneuver support, and escalation of force management, with reliable effects well beyond small arms range. The ADS is the first directed-energy non-lethal weapon to be ready for fielding by DOD. It is a pathfinder in proving this kind of weapon's potential military effectiveness while meeting the critical standards of human effects, safety, legal, treaty, policy and public affairs reviews.

The ADS ACTD has successfully undergone legal, treaty and U.S. Central Command rules of engagement reviews. The Joint Requirements Oversight Council has formally approved the ACTD concept of operations. DOD has provided policy memorandums supporting acquisition of ADS.

Two versions of ADS have been developed. System 1 is a vehicle-based system, deployed on a hybrid electric High Mobility Multi-Wheeled Vehicle (HMMWV). System 2 is a containerized version more suited to a fixed operating location, such as covering an access control point or a portion of a perimeter fence. Several requests to field System 1 to the Central Command area of responsibility have been received including:

- Southern European Task Force request for deployment to Operation Enduring Freedom (2004): System was not ready for deployment at the time of the request.
- Army Rapid Equipping Force initiative in response to urgent need statement to field System 1 with 18th MP Brigade for Operation Iraqi Freedom deployment (2005–2006): System available for deployment; however, the Office of the Under Secretary of Defense for Policy deemed the intended mission

(detainee operations) not politically tenable, hence it has not been fielded for operational use.

The ADS has accomplished multiple "firsts." It is the first weapon that has successfully completed formally-evaluated directed energy counter-personnel Joint Military Utility Assessments, across three separate bases and environments, using twenty different scenarios with multiple iterations. There have been 3,500 full body shots recorded in four field exercises with no significant injuries. The ADS has conducted the first urban environment testing with seven separate vignettes at Creech Air Force Base, Nevada, and Fort Benning, Georgia.

The ADS program has completed an evaluation of nine separate countermeasure techniques and the first use of maritime, over the water shots, against five types of U.S. Coast Guard boats. ADS System 1 has over 1,100 hours of operation.

Issues. The ADS ACTD is principally focused on proving the utility of a scalable electronic waveform, with joint applicability, which can be integrated into an aircraft, ship, or ground vehicle using various ranges, power, and effects criteria. This electronic waveform works well on test subjects; however, the deterrent non-lethal effects, instantaneous heating of the skin, are new and different, providing a novel battlefield effect that will require significant education and awareness for military members and the general public to understand.

The ADS has the challenge to demonstrate and train with volunteers at their home station. Lacking precedents for this type of weapon, it typically takes one to three months to satisfy a base or station and local unit's questions prior to receiving approval for live fire evaluations. This process is time consuming but achievable.

Schedule and Funding. ADS System 1, hand-built on a hybrid-electric HMMWV, cost approximately $10.5 million dollars. There are limited efforts underway to reduce cost, size, and weight to more acceptable levels. Until ADS is actually used, the military services are reluctant to seriously consider investing in this type of directed energy weapon. Deploying ADS for first-time use will be precedent setting.

As is the case with most new weapons, first time use of ADS will require approval by the Secretary of Defense.

The ADS ACTD schedule was unable to accelerate its testing fast enough to provide data to the services in time to consider in their fiscal year 2008 POM. However, ADS is now ready for deployment and could be included in the POM for 2010 as a deployable directed energy weapon system. However, as stated earlier, ADS has not been approved for operational use in ongoing contingency operations.

Counter-Improvised Explosive Device

The Joint Improvised Explosive Device Defeat Organization and the Office of Naval Research have sponsored development of breadboard technology that permits the assessment of the effects of directed radio frequency (RF) on RF and non-RF components (such as timers and infrared sensors) of IED triggers. The goal has been to achieve mine or IED neutralization through controlled dud or detonation at safe ranges. Initial assessment of the technology provided the means to offer a portal protection system that could prevent entry of bombs into secure areas by neutralizing hot wire initiators and electro-explosive devices.

A low-rate production of a weaponized HPM breadboard system has provided a vehicle mounted version that can self protect a vehicle or a convoy. The IED neutralizer, based on commercial off-the-shelf components, has been assessed in theater operations. A variant is being developed for possible robotic operations.

Funding for this promising technology application is currently about $2–2.5 million per year, and the objective is to transition within five years to Army program implementation.

Counter-Vehicle

RF-directed energy is projected to have utility in countering vehicles through engaging and disrupting the occupants similar to ADS applications or by stopping the engines (electronic controls). The JNLWD, along with the Department of Justice, is sponsoring joint research at the Army Research Lab, the Naval Research Lab, and the Air Force Research Lab, to collect data on the most effective combination of power and frequency modulation to enforce the development of a vehicle engine stopper for ranges of interest, and to develop a demonstrator system.

Counter-Rockets, Artillery, and Mortars

Increases in power density (W/cm2) that are required to disable vehicles, coupled with accurate directional pointing and tracking of the RF array, could provide a capability to counter rockets, artillery, and mortars. This capability could be achieved by disrupting the electronics of inbound guided rockets and/or artillery or mortar that rely on fusing for weapons effectiveness. An early capability to counter terrorist missiles that might be used against large airborne targets has been demonstrated. Waveforms selected are tailored to specific enemy missile designs and are viewed to be effective against common electromagnetic shielding techniques.

C-C4ISR

HPM could be used to disrupt electro-optical sensors and onboard electronics of elements of surveillance and reconnaissance systems. In addition, disruption of computer-based assets, perhaps without knowledge of the cause, is possible with dedicated HPM applications.

High-Power Microwave Systems Effects

The process to assess the effects of high-powered microwave on a target has to include the full process from power source to target response. Figure 12 illustrates the chain from source to response and includes some of the drivers of the output of each step in the chain of events. Assessing each of these activities and the coupling with the target environment will be essential in determining the military utility of the respective system concept. However, the information is target-specific (threat-sensitive) and, as a consequence, stove piped and/or may not be generally available for the potential DOD user set. Because the Active Denial System was an early ACTD with humans as the non-lethal target, there has been a dedicated effort to assess the non-lethal suitability and effectiveness of operation and promulgate the results of the analyses.

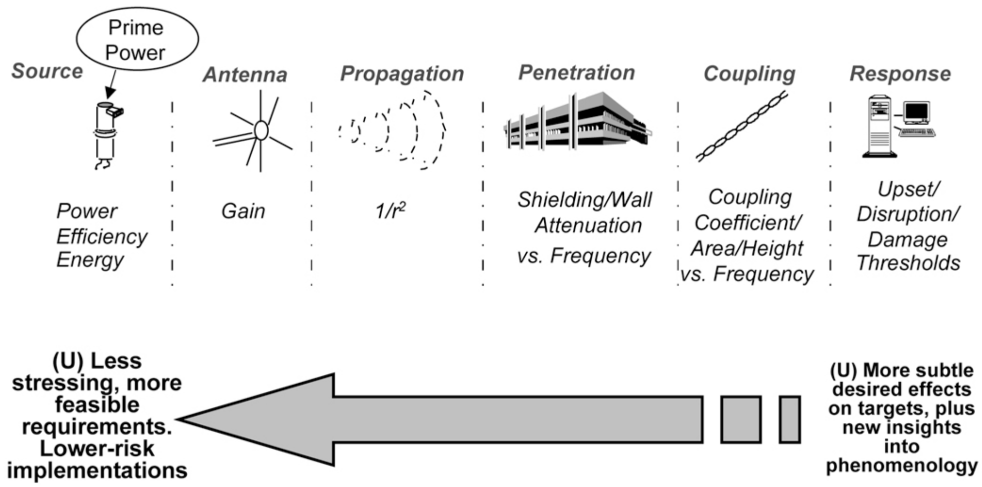

Figure 12. Source-to-Target Response

The ADS employs millimeter wave technology to repel individuals without causing injury. This capability enables users to stop, deter, and turn back adversaries without the use of lethal force. The system also disrupts an assailant's ability to effectively use a weapon. The ADS provides the ability to control outbreaks of violence, minimize collateral damage, and ultimately saves lives.

The ADS emits a 95 GHz non-ionizing electromagnetic beam of energy that penetrates approximately 1/64 of an inch into human skin tissue, where nerve receptors are concentrated. Within seconds, the beam will heat the exposed skin tissue to a level where intolerable pain is experienced and natural defense mechanisms take over. This intense heating sensation stops only if the individual moves out of the beam's path or if the beam is turned off. The sensation caused by the system has been described by test subjects as feeling like touching a hot frying pan or the intense radiant heat from a fire.

Findings and Recommendations

- A rigorous analytical effort is required to identify those capability gaps for which HPM weapons are likely to be the most effective solution.
    - *USD (AT&L), the Director, Program Analysis and Evaluation, and the military departments should establish programs analyzing the cost and benefit of promising applications of high-power microwave systems to fill identified weapons needs.*
- High-power microwave is the preferred solution for many non-lethal applications to include active denial, vehicle denial, and electronic defeat systems.
    - *The designated executive agent (Marine Corps) for non-lethal weapons should provide a vision and strategic plan for exploiting HPM technologies for non-lethal applications.*
- Research and development should be concentrated on those applications where rigorous assessment shows that an HPM weapon is the preferred solution vice a kinetic or laser weapon.
    - *USD (AT&L) and the Director, Program Analysis and Evaluation, should establish a program analyzing the cost and benefit of promising applications of HPM to fill identified weapons needs. A coherent weapons effects program, available to all services and agencies, is an essential underpinning of cost/benefit analyses.*
- S&T funding for HPM applications should be concentrated on a defined set of applications meeting high priority needs.
    - *USD (AT&L) should task the military departments to provide road maps to move demonstrated technologies to fielded capabilities in accordance with priorities established by combatant commands and force providers.*
- The structure of programs directed at fielding capabilities is currently not consistent with the resources or the number and scope of HPM activities in the Department.

- *USD (AT&L) should task DDR&E to prioritize efforts so that a coherent set of programs can be aligned to move to fielded capabilities.*

- There is inadequate communication on legal and policy support for HPM non-lethal weapons development, deployment, and employment.

  - *The Under Secretary of Defense for Policy should publish unclassified clarification of the legal and policy implications for non-lethal HPM applications.*

Chapter 4. Industrial Base

In their seminal book *Keeping the Edge: Managing Defense for the Future*, John White and Ashton Carter credited the U.S. success in counterbalancing the numerical superiority of Soviet forces by the capabilities of America's high technology military systems. The key to this success was attributed to the nation's aggressive pursuit of military R&D, coupled with a high technology industrial base, while concurrently denying that technology to opponents.

Today, however, the nation faces the threats of both superior numbers in some parts of the world and the ubiquitous nature of high technology information available to virtually any state via the global cyber world. This environment requires U.S. defense forces to operate in both the legacy mode of the last century and the advanced technology era of the 21st century. To continue to lead in R&D and to maintain U.S. superiority, a necessary condition is a strong and flexible industrial base. In the assessment that follows, the industrial base is divided into four components, recognizing that these components are not mutually exclusive: industry firms, funding, market potential, and personnel.

Industrial Firms

During the Cold War, a large number of prime contractors concentrated on defense systems. In the decade of the 1990s, with the demise of the Soviet block, major mergers and buy-outs resulted in a dramatic reduction in the number of defense-oriented contractors. For example, a recent study found that defense prime contractors that numbered 36 in 1993 had shrunk to only 8 by the turn of the century. The positive aspect of this phenomenon is less defense funds are needed to maintain viable contractors vying for defense contracts. However, on the negative side is a reduction in serious competition for defense contracts and a large number of 2^{nd} and 3^{rd} tier companies out of work or turning to non-defense projects. In addition, the technical depth in many critical areas at the remaining large defense contractors has been lost so that in specific areas, there is an obvious loss of viability.

Prime contractors depend on sub-tier vendors to provide the building blocks essential to major systems—items that range from fasteners and special cabling to black boxes and small, but critical, electrical parts. Furthermore, if a vendor can supply a small number of parts needed for an R&D project, there might be no capability to ramp up to full production should the prototype be turned into a full scale production order. For example, two different prime contractors described to the task force the need to go to foreign sources for critical, high-quality parts needed in the development of high-energy lasers.

For lasers, the technical-base situation is mixed. There are a wide variety of companies, including both large aerospace companies and smaller companies, with expertise in solid-state lasers. There are two large aerospace companies with proven capabilities to build high-energy COIL lasers. The nation used to have a significant capability to build HF/DF chemical lasers, but no significant-sized HF/DF laser has been built since the THEL laser was completed in 1999; thus, it is unclear what current capability exists. Most of the technical expertise in FELs resides in national laboratories and universities; there is little demonstrated capability in industry to design and build a high-energy FEL. There is a growing community of organizations with expertise in fiber lasers, although several of the leading organizations are foreign.

Funding

In the aftermath of Vietnam, the defense budget gave high priority to funding R&D of advanced technology for integration into existing systems. Laser range-finders and target designators, millimeter wave employment in communication systems, and basic research on high-powered lasers and microwave weapons were some of the results achieved. In the early 1990s, Operation Desert Storm demonstrated the fruits of these efforts in the relatively rapid success of U.S. forces who were aided by high technology systems that guided U.S. missiles, provided superb accuracy for tank guns, allowed ground forces to navigate the desert with unique accuracy, and confounded an enemy who was credited with being strong and capable.

Now the nation finds itself in conflict with non-state enemies who use non-combatants as shields, wear no uniforms, are willing to sacrifice themselves to achieve great lethality, and obey none of the international conventions for warfare. U.S. forces are searching for ways to distinguish the enemy from non-combatant civilians and for defending themselves from suicide attackers that care nothing about collateral damage. Directed energy appears to have the potential to provide U.S. forces with some of the advanced capability to answer the needs.

At present there are few formal programs for directed energy, with the majority of funding in research, rather than supported systems. As a result, the industrial base for directed energy is small and at risk. One solution to this weakness is to clearly define directed energy applications that have a high potential for payoff on the battlefield as a complement to kinetic energy weapons or as a stand-alone operational system. Currently there is little user demand, which raises a question of the market potential for directed energy systems.

Market Potential

Research and development is considered the necessary lifeblood for new systems. However, R&D is not the function that brings margin to the operating profit of the contractors. Production is essential to profit and, thus, to shareholder support. Subcontractors and vendors, as well as the prime contractors, depend on the sales that come with full-scale production. When R&D is continued for long periods without a promise of future production quantities, the small vendors cannot continue to operate and plan for future business. In defense systems, the key to future business is the existence of funded programs.

Military commanders understand the lethality and employment of kinetic energy weapons. Computer war games and battlefield maneuvers based on well-used weapons effects data are superb training aids. Recent actual battles have served to confirm what the training aids projected. Weapons based on new technology, such as high-powered microwave or high-powered lasers, do not have weapons effects manuals as yet. The weapons effects of directed energy systems may not be as visible as an explosion of a kinetic round, even though the actual damage done destroys the target’s ability to operate.

Some directed energy systems are designed to be non-lethal. As a consequence of this new phenomenon, commanders have been reluctant to opt for directed energy weapons. Moreover, they question whether the well-known kinetic weapon is to be replaced with a little-known directed energy system, or will the addition of a directed energy weapon compete for space in the already crowded crew compartments? To be successful in establishing viable programs for directed energy operating systems, there needs to be a strong effort to demonstrate to the user community the significant advantages of these systems. Only then will there be support for programs, which is evidence of market potential, and in turn influences the viability of the industrial base.

Personnel

A qualified workforce is central to industrial capability. More often than not, new industry is sought after by communities in order to provide work for its inhabitants and to increase the tax base. Many such communities have excellent pools of trained people. However, in the case of new technologies (such as directed energy) that require scientific research and innovative engineers, the need for exceptionally qualified and experienced people is critical to successful development of products.

In briefings to the task force, prime contractors made the point that high tech groups of subject matter scientists and experienced engineers with a clear vision of what is needed by the customer generally provide better products on schedule and within budget. However, if R&D is not followed in a reasonable time by programs and orders for products, then the experienced teams are broken up and their synergy lost. The industrial base of people is at risk when untimely delays between prototype and production occur. The history of directed energy technology becoming integrated into military operating systems exemplifies this point.

The ADS, the THEL, and STINGRAY are a few examples of directed energy systems that achieved success as demonstrators, but have not yet resulted in funded programs. One prime contractor stated: that at the prime level the directed energy industrial base is heavily dependent upon ABL and pointed out that if ABL doesn't succeed for production, there is high risk of the loss of design and system engineering talent. A further concern of this contractor is the fact that in some key areas, there is only one 2nd and 3rd tier supplier, who is unable to invest to stay in the queue for uncertain orders. If designing and employing directed energy as weapons and in supporting systems indeed offers good leverage for the U.S .military forces, it is important to understand the important role played by high technology teams for both research and development and industrial base surge.

Findings and Recommendations

- The lack of directed energy production programs or the serious prospect of significant production programs has jeopardized the supporting industrial base. There is essentially one U.S. vendor capable of supplying deformable mirrors.
  - *The Deputy Secretary of Defense should direct the military departments to provide overall vision and strategic plans for developing relevant directed energy capabilities that can provide visibility into the likely future business case for sustaining directed energy industry capabilities.*
- Several primes are using foreign sources for some high technology items to support the continued development of a solid state laser.
  - *The USD (AT&L) should assess the long-term reliability and acceptability of foreign sources for essential components of directed energy systems.*
- The nation's capability to fabricate and coat large high-power optics is sufficiently atrophied that obtaining a replacement for the ABL output window would be problematic.
  - *The Secretary of the Air Force should direct an urgent review of supply sources for large high-power optics of the class needed for an ABL class system.*
- The nation's technical capabilities in HEL components and sub-systems are thin and have, in some cases, atrophied. The situation in large high-power optics and beam control is particularly fragile depending on a single vendor at best.

  USD (AT&L) should direct a survey of laser component capability and produce a plan for sustaining access to the required capability.

Chapter 5. Summary of Findings and Recommendations

Bottom Lines

- Directed energy employment needs to be clearly described in concepts of operation as the basis for decisions relating to technical, employment, policy planning and priorities.
  - *The Under Secretary of Defense for Acquisition, Technology and Logistics (USD [AT&L]) should require that the military departments provide a concept of operation for each proposed laser and HPM weapons system.*
- For each capability gap where directed energy is a proposed solution, the directed energy solution should be assessed against available kinetic or other approaches to filling the gap.
  - *USD (AT&L), the Director, Program Analysis and Evaluation, and the military departments should establish programs analyzing the cost and benefit of promising applications of laser and HPM weapons to fill identified capability needs.*
- Research and development funding should be focused on those directed energy solutions where rigorous analyses identify directed energy as the most promising solution to a priority need and concentrated for progress rather than spread over a large number of projects.
  - *USD (AT&L) should task the military departments to provide road maps (strategic plans) to move demonstrated technologies to fielded capabilities in accordance with priorities established by combatant commands and force providers.*
- S&T funding for laser weapons should be heavily focused on high power solid state lasers and significantly improved beam control for appropriate applications and on concentrated development of free electron lasers for ship defense.

- *The Director, Defense Research and Engineering should give high priority to S&T activities addressing high power solid state laser development and accompanying beam quality and beam control development.*

▪ The Department needs an authoritative single source data base for directed energy effects similar to the munitions effects manual for kinetic weapons. Development of meaningful concepts of operations and analyses of military utility require the foundation of credible weapons effects data and assessments.

- *The Deputy Secretary of Defense should assign responsibility to a military department to develop a laser and high power microwave effects manual.*

▪ The development of laser and high power microwave technologies and systems available to potential adversaries poses a new set of challenges to U.S. military force capabilities.

- *The Under Secretary of Defense for Intelligence (USD [I]) should:*
    - *Produce a needs statement for the National Intelligence Community that details the information support that is required to perform quality threat assessment and identify development opportunities and needs.*
    - *Designate a member of the USD (I) staff to be a focal point for advocating improvement in all dimensions of directed energy intelligence.*
- *The Director, Defense Intelligence Agency should undertake a specific program to discover and assess emerging laser and high power microwave capabilities available to the full range of potential adversaries. The program needs to be supported by people with expertise in directed energy technologies and applications.*

▪ The Department needs a concerted education effort to replace the “death ray” myth of directed weapons with a comprehensive understanding of the potential benefits and limitations of low-, medium-, and high-power laser applications, high power microwave, and millimeter wave applications.

- *The military departments should accelerate efforts to credibly assess effects on human targets, and widely publicize the facts.*

Threat

- The development of laser and high power microwave technologies and systems available to potential adversaries poses a new set of challenges to U.S. military force capabilities.
  - *The Under Secretary of Defense for Intelligence (USD [I]) should:*
    - *Produce a needs statement for the National Intelligence Community that details the information support that is required to perform quality threat assessment and identify development opportunities and needs.*
    - *Designate a member of the USD (I) staff to be a focal point for advocating improvement in all dimensions of directed energy intelligence.*
  - *The Director, Defense Intelligence Agency should undertake a specific program to discover and assess emerging laser and high power microwave capabilities available to the full range of potential adversaries. The program needs to be supported by people with expertise in directed energy technologies and applications.*
- Space-based and airborne sensor development programs and communications satellites should include protection against laser systems that can dazzle or destroy sensor capabilities.
  - *The Secretary of the Air Force; the Commander, Air Force Space Command; and the Director, National Reconnaissance Office should require a full analysis of the survivability of essential space-based capabilities assuming adversary capabilities to attack satellites with directed energy weapons.*
- Electronic components of essential communications networks are susceptible to damage and disruption from high power microwave systems.
  - *The Assistant Secretary of Defense for Networks and Information Integration (ASD (NII)) and the Director, DISA should require a*

full analysis of the survivability of essential communications networks assuming adversary capabilities to attack electronic components with directed energy weapons.

- *The Under Secretary of Defense for Acquisition, Technology and Logistics (USD (AT&L)) should direct that:*
  - *New systems include protection against high power microwave disruption.*
  - *The ASD (NII) should direct an assessment of the feasibility of protecting existing command and control networks against directed energy attacks.*

High Power Lasers

- There needs to be a rigorous analytical effort to identify those capability gaps for which laser weapons are likely to be the most effective solution.
  - *The Deputy Secretary of Defense should direct that the military departments provide rigorous analyses to determine where capability gaps are best addressed by directed energy weapons and provide roadmaps of the path to developing such capabilities.*
- Enhanced modeling-and-simulation capabilities for laser systems are needed to reduce development times and costs and to ensure that operational and logistics considerations are understood and addressed.
  - *USD (AT&L) should direct development of non-proprietary modeling and simulation capabilities to be made available to government and contractors.*
  - There needs to be an authoritative single source data base for directed energy effects similar to the munitions effects manual for kinetic weapons.
- Research and development needs to be concentrated on those applications where rigorous assessment shows that a laser weapon is the preferred solution vice a kinetic weapon.

- *USD (AT&L), the Director, Program Analysis and Evaluation, and the military departments should establish programs analyzing the cost and benefit of promising applications of laser energy to fill identified weapons needs.*

- S&T funding for laser application is fragmented across a wide range of explorations and activities without established priorities.

  - *USD (AT&L) should task the Director, Defense Research and Engineering (DDR&E) to develop directed energy S&T priorities for FY09 and beyond so that projects and programs that support the identified R&D can be properly supported.*

- S&T funding for laser weapons should be heavily focused on solid-state and fiber lasers with at least 100 kilowatts of power and with significantly improved beam quality and control.

  - *DDR&E should give high priority to S&T activities addressing high power solid state laser development, fiber beam combining, and accompanying beam quality and beam control development.*

- S&T funding for low and medium power laser applications should be concentrated on a defined set of applications meeting high priority needs to include defeating UAV platform mission capabilities, defeat of MANPADS and defeat of rockets, artillery and mortars.

  - *USD (AT&L) should task the military departments to provide road maps (strategic plans) to move demonstrated technologies to fielded capabilities in accordance with priorities established by combatant commands and force providers.*

- High powered chemical lasers, as a more mature technology, should be the preferred first generation solution for high energy fixed or very large platform applications.

  - *USD(AT&L), with support from the Air Force, should identify and support future needs other than ABL and Tactical Airborne Laser and should realign funding for high power chemical lasers to a considered balance between technical development and efforts to field operational systems.*

- The fragmented programs associated with developing a free-electron capability for ship defense should be coalesced into a coherent program directed at providing a fielded system.
  - *The Secretary of the Navy should direct transition to an "Innovative Naval Prototype" program to integrate technology programs into a program that has the potential to develop a fleet defense system.*
- Recent S&T accomplishments, although technically impressive, have often demonstrated performance well short of that required for DOD applications and have done so in configurations that have not addressed manufacturability, packaging, maintainability, and other similar concerns that are critical for making HELs operationally acceptable.
  - *DDR&E should require that S&T work include focus on operational and logistics aspects. The cost/benefit analyses for each projected application should include consideration of operability and sustainment in the battlespace.*
- Enhanced modeling-and-simulation capabilities for laser systems are needed to reduce development times and costs and to ensure that operational and logistics considerations are understood and addressed.
  - *USD (AT&L) should direct development of non-proprietary modeling and simulation capabilities to be made available to government and contractors.*
- There needs to be an authoritative single source data base for directed energy effects similar to the munitions effects manual for kinetic weapons.
  - *The Deputy Secretary of Defense should assign responsibility to a military department to develop a laser (and HPM) effects manual.*
- A concerted education effort is needed to replace the "death ray" myth of directed weapons with a comprehensive understanding of the potential benefits and limitations of low, medium, and high power laser and high power microwave applications.
  - *The military departments should accelerate efforts to credibly assess effects on human targets, and widely publicize the facts.*

High Power Microwave

- A rigorous analytical effort is required to identify those capability gaps for which HPM weapons are likely to be the most effective solution.
  - *USD (AT&L), the Director, Program Analysis and Evaluation, and the military departments should establish programs analyzing the cost and benefit of promising applications of high power microwave systems to fill identified weapons needs.*
- High power microwave is the preferred solution for many non-lethal applications to include active denial, vehicle denial, and electronic defeat systems.
  - *The designated Executive Agent (Marine Corps) for non-lethal weapons should provide a vision and strategic plan for exploiting HPM technologies for non-lethal applications.*
- Research and development should be concentrated on those applications where rigorous assessment shows that an HPM weapon is the preferred solution vice a kinetic or laser weapon.
  - *USD (AT&L) and the Director, Program Analysis and Evaluation should establish a program analyzing the cost and benefit of promising applications of HPM to fill identified weapons needs. A coherent weapons effects program, available to all services and agencies, is an essential underpinning of cost/benefit analyses.*
- S&T funding for HPM applications should be concentrated on a defined set of applications meeting high priority needs.
  - *USD (AT&L) should task the military departments to provide road maps to move demonstrated technologies to fielded capabilities in accordance with priorities established by combatant commands and force providers.*
- The structure of programs directed at fielding capabilities is currently not consistent with the resources or the number and scope of HPM activities in the Department.
  - *USD (AT&L) should task DDR&E to prioritize efforts so that a coherent set of programs can be aligned to move to fielded capabilities.*

- There is inadequate communication on legal and policy support for HPM non-lethal weapons development, deployment, and employment.
  - *The Under Secretary of Defense for Policy should publish unclassified clarification of the legal and policy implications for non-lethal HPM applications.*

Industrial Base

- The lack of directed energy production programs or the serious prospect of significant production programs has jeopardized the supporting industrial base. There is essentially one U.S. vendor capable of supplying deformable mirrors.
  - *The Deputy Secretary of Defense should direct the military departments to provide overall vision and strategic plans for developing relevant directed energy capabilities that can provide visibility into the likely future business case for sustaining directed energy industry capabilities.*
- Several primes are using foreign sources for some high technology items to support the continued development of a solid state laser.
  - *The USD (AT&L) should assess the long term reliability and acceptability of foreign sources for essential components of directed energy systems.*
- The nation's capability to fabricate and coat large high-power optics is sufficiently atrophied that obtaining a replacement for the ABL output window would be problematic.
  - *The Secretary of the Air Force should direct an urgent review of supply sources for large high-power optics of the class needed for an ABL class system.*
- The nation's technical capabilities in HEL components and sub-systems are thin and have, in some cases, atrophied. The situation in large high-power optics and beam control is particularly fragile depending on a single vendor at best.
  - *USD (AT&L) should direct a survey of laser component capability and produce a plan for sustaining access to the required capability.*

Appendix A. Terms of Reference

THE UNDER SECRETARY OF DEFENSE

3010 DEFENSE PENTAGON
WASHINGTON, DC 20301-3010

ACQUISITION,
TECHNOLOGY
AND LOGISTICS

OCT 30 2006

MEMORANDUM FOR CHAIRMAN, DEFENSE SCIENCE BOARD

SUBJECT: Terms of Reference – Defense Science Board (DSB) Task Force on Directed Energy (DE) Weapon Systems and Technology Applications

You are requested to form a DSB Task Force on DE Weapon Systems and Technology Applications. The technological maturity of directed energy weapon systems indicates the Military Departments may be ready to begin integration into operational forces at all levels of military operations.

In recent years, the Military Departments initiated and are currently pursuing a variety of programs to develop applications for DE technologies for a wide variety of military uses. Interest has grown in the operational use of DE technology for mission areas such as airborne- and ground-based precision attack, missile defense, expeditionary installation defense, homeland critical infrastructure defense, and non-lethal applications. A wide variety of technology advancements support these system developments -- both in commercial industries and military laboratories. DE technology has developed rapidly in key enabling sub-systems areas as well.

DE systems appear to provide the Department with unique opportunities to augment or improve operational capabilities in several areas. However, with the development of DE technologies in military and commercial applications, potential adversaries may have the ability to develop offensive DE systems with equal or greater lethality than current U.S. systems. In order for the Department to effectively incorporate DE weapon systems and technologies into offensive and defensive war fighting operations, the Task Force is to:

1. Review all surface, sub-surface, air, and space DE programs in the Department and other organizations and identify duplicative and/or redundant efforts concerning research, development, procurement, and deployment of DE systems and capabilities. To the maximum extent practicable, the task force will also review the findings from the FY 2004 Strategic Planning Guidance study of DE programs, the OSD DE roadmap, and the DDR&E DE net assessment.

2. Examine recent supporting technology advancements and their applications with respect to supporting military DE weapon system developments.

3. Develop potential tactical and strategic DE system applications and identify processes required to implement these potentials.

4. Determine what remains to be done to "weaponize" DE systems and technologies, including measures needed to allow them to operate and be supported in applicable combat theater environments.

5. Assess DE operational concepts, impacts, and limitations while considering potential legal, treaty, and policy compliance issues concerning DE systems employment.

6. Determine Department vulnerabilities and capability gaps in regards to offensive use of DE weapons by state and non-state actors against U.S. personnel, systems, enablers, and critical capabilities across the full spectrum of military operations including undersea, sea surface, land, air, and space.

7. Make recommendations on:

a. Research efforts not currently being addressed by the Department, including supporting technologies that enable military DE applications.

b. Potential tactical and strategic impact of DE systems on future military operations compared to current kinetic and electronic systems.

c. Potential strategic advantage DE weapons can provide with regards to the delivery of precision effects, decreased collateral damage, limiting unintended effects, and decreasing post-combat reconstitution costs and efforts.

d. Capabilities of the U.S. defense industrial base to support development of DE systems.

e. Transition paths or roadmap for DE weapons development and military applications.

f. Incorporating DE hardening and protection requirements into the Department's current and future weapon system acquisition and procurement programs.

g. Legal, treaty, and policy issues concerning DE employment in military operations.

h. Optimum way forward to fuse DE efforts within the Department and outside organizations.

i. Establishing Department DE policies to preclude unnecessary expenditure of human and fiscal resources.

j. Protection requirements of Department personnel from friendly, allied, and adversary use of DE weapons and systems on the battlefield.

The study will be sponsored by me as the Under Secretary of Defense for Acquisition, Technology, and Logistics, the Secretary of the Air Force, and DDR&E. General (Ret) Larry Welch, and Dr. Bob Hermann will serve as the co-Chairmen of the Task Force. Lieutenant Colonel Jimmy Wallace, USAF, Air Force Combat Support Office and Dr Thomas Spencer, Office of DDR&E, will serve as co-Executive Secretaries. Major Chad Lominac, USAF, will serve as the DSB Secretariat Representative.

The final report will be due no later than May 31, 2007. The Task Force shall have access to requested classified information for development of the assessment and recommendations.

The Task Force will be operated in accordance with the provisions of P.L. 92-463, the "Federal Advisory Committee Act," and DoD Directive 5105.4, "The DoD Federal Advisory Committee Management Program." It is not anticipated this Task Force will need to go into any "particular matters" within the meaning of title 18, United States Code, section 208, nor will it cause any member to be placed in the position of acting as procurement official.

Kenneth J. Krieg

Appendix B. Task Force Membership

CO-CHAIRS

Name	Affiliation
Gen Larry D. Welch	Institute for Defense Analysis, Inc.
Dr. Robert Hermann	Private Consultant

MEMBERS

Mr. Richard Haver	Northrop Grumman Corporation
Gen Robert Marsh, USAF(Ret)	Private Consultant
GEN Glenn Otis, USA (Ret)	Private Consultant
Dr. Bruce Pierce	Photon Research Associates, Inc.
Dr. Charles A. Primmerman	MIT Lincoln Laboratory
Dr. Robert Strickler	Private Consultant
Dr. Richard Wagner	Los Alamos National Laboratories

GOVERNMENT ADVISORS

Col John Costa, USAF	
Mr. Richard Gullickson, SES	Office of Naval Research, DTRA
Col Craig Hughes, USAF	Office of the Secretary of Defense, S&T
Dr. Spiro Lekoudis	Office of the Secretary of Defense, S&T
Ms. Susan Levine	Joint Non-Lethal Weapons Directorate
Dr. David C. Stoudt	Naval Surface Warfare Center, Dahlgren Division

EXECUTIVE SECRETARIES

Dr. Thomas Spencer	Office of the Secretary of Defense, AT&L
Lt Col Jimmy Wallace, USAF Reserve	HQ USAF / Air Force Combat Support Office

DSB REPRESENTATIVE

Maj Charles Lominac	Office of the Secretary of Defense, AT&L

STAFF

Mr. Anthony L. Johnson	Strategic Analysis Inc.
Ms. Carla King	Strategic Analysis Inc.

Appendix C. Presentations to the Task Force

Name	Topic
NOVEMBER 2 – 3, 2006	
Lt Col Jimmy Wallace, USAF Reserve	2001 HEL DSB Study Review
Dr. David Stoudt	Navy and Marine Corps Directed Energy Programs
Mr. Elliott Lehman	DIA Threat Briefing
Dr. Thomas Spencer	DOD DE Roadmap
Dr. Thomas Spencer	DE S&T Overview
DECEMBER 4 – 5, 2006	
Col Craig A. Hughes & Mr. Lloyd Feldman	Force Transformation's Directed Energy Systems Overview
Dr. Joseph Mangano	High Power Fiber Lasers driving Adaptive Photonic Phase-Locked Elements (APPLE)
Dr. Donald Woodbury	High Energy Liquid Laser Area Defense System (HELLADS)
Mr. Michael Cochrane	Directed Energy Way Ahead
Dr. Gary Wood, Mr. John Tatum, Mr. John Hopkins, & Mr. Steve Bayne	Army Research Laboratory Directed Energy Programs
Ms. Mary J. Miller	Army Science & Technology: Directed Energy Efforts
Col John Daniels & Dr. Lamberson	Airborne Laser Program Status
Dr. Jason Marshall	Overview of the Advanced Tactical Laser ACTD and Advanced COIL Technology Development
JANUARY 9 – 10, 2007	
Mr. Mark W. Neic	JTO overview, FY07 efforts and funding profile & HEL/JTO Strategic/Operational Levels brief
Ms. Susan LeVine	Non-Lethal Directed Energy Weapons
Mr. Richard Gullickson	Applications of Directed Energy for WMD Detection

Mr. Mike Booen	Raytheon DE Perspective
Mr. Jay Kistler	OSD Joint Forces Office DE Overview
Mr. Gary Fitzmire	Presentation to the DSB Directed Energy Task Force
Jim Alley	Overview of Lethality Analysis Approach for Non-Kinetic Damage Mechanisms
Mr. Mark Stephen	L-3 Communications Directed Energy Programs and Challenges
Mr. Charles Gilman & Dr. Robert Peterkin	SAIC Perspectives on DE Technology and Transition to Weapons Systems
Patrick Garret	Adversary Space Doctrine

FEBRUARY 13, 200

CAPT David H. Kiel, USN	Surface Navy HEL vision and Initial Laser Weapon System
Mr. Dan Wildt	Northrop Grumman Space Technology Directed Energy Programs
Mr. Castro Giovanni	Directed Energy Technology and Weaponization: ATK Activity and Perspective

MARCH 15 – 16, 2007

Mr. Doug Graham	Presentation to the DSB Task Force on Directed Energy
Col JD Clem. USAF	Directed Energy Aspirations for the Next Generation Gunship & AFSOC/SOCOM
Mr. Francis Corbett	High Energy Laser – Directed Energy Weapon Development
Dr. Kenneth Watman	Findings from the A8 Policy Summit
Col Dave Wooden, USAF	ACC Directed Energy Way Ahead
Col Edwards, USAF	AF DETF update
Mr. Amit Kapadia & Mr. Lori Decker	DE Science & Technology and DE Test & Evaluation Capability
Mr. Brian Duffek	AFSPACE

APRIL 27, 2007

Mr. Hennessey & Lt Col Ki Kang, USAF	SAF/AAZ Brief
Mr. Jorge Beraun	AFRL/DETP Brief
Dr. Lew DeSandre	FEL Navy S&T Program for High Energy Lasers and Beam Control
Dr. Frank E. Peterkin & Dr. Brian J. Hankla	DETO HEL Lethality on Naval Targets

MAY 23, 2007

Mr. Robert Turman	An Overview of DE at Sandia
Dr. Robert Yamamoto	Lawrence Livermore DE Programs

Appendix D. Organization

The DOD currently oversees approximately $1.1 billion in directed energy investment. These resources are concentrated on developing technology to ultimately be introduced into systems to fill DOD capability gaps. The organizational structure for directed energy weapons and technology development is spread across the military services and defense agencies. At the top level, the organizations encompass the Army, Air Force, Navy, and Marines research and development and acquisition structures; DOD agencies, such as the Defense Advanced Research Projects Agency and Missile Defense Agency; and joint components, such as the Joint Non-Lethal Weapons Directorate, the High Energy Laser Technology Council, and the High Energy Laser Joint Technology Office.

In addition, the intelligence community is involved in performing directed energy threat assessments. The Defense Intelligence Agency, the individual service intelligence agencies, such as the National Ground Intelligence Center and the National Air and Space Intelligence Center, compile and disseminate assessments of directed energy capabilities around the world.

This chapter provides an overview of organizations involved with directed energy technology and applications, though it is not intended to be exhaustive. Joint and defense agency organizations discussed include:

- Director, Defense Research and Engineering
  - Provides oversight and direction of the DOD directed energy S&T efforts.
- Advanced System and Concept Office
  - provides policies, plans, procedures, and guidance for ACTDs
- High Energy Laser Joint Technology Office
  - develops and manages a joint program to develop laser technology for potential weapons applications

  - managed by the Air Force
- Joint Non-Lethal Weapons Directorate
  - provides day-to-day management for the DOD Non-Lethal Weapons Executive Agent, the Marine Corps
- Defense Advanced Research Projects Agency
  - manages and directs selected R&D projects
- Missile Defense Agency
  - oversees and directs the ABL program

Director, Defense Research and Engineering

The Director, Defense Research and Engineering is responsible the direction and content of the DOD science and technology program. DDR&E establishes the vision, strategy, and priorities and oversees program management, execution, and output. DDR&E is responsible for budget activities (BA) 1–4 (BA 4 funds Technical Readiness Levels 5 and 6) leading up to Milestone B in the acquisition process (the point where technology transitions from a technology development effort into the system development and demonstration phase). Budget activities 1–4 are also widely referred to as research (6.1), exploratory development (6.2), and advanced development (6.3.). DDR&E oversees laboratories, research, development, engineering centers, and warfare centers operated by the military departments or other Department of Defense components, federally funded research and development centers, and university affiliated research centers. DDR&E also oversees DARPA.

For fiscal year 2007, the directed energy S&T investment in the Office of the Secretary of Defense (OSD), across budget activities 1–4 is approximately $1.1 billion. Figure D-1 shows the directed energy investment as a function of service and component. As shown in Figure 28, the majority of the investment in BA 4 is in the Missile Defense Agency Airborne Laser Program, an investment of approximately $630 million. At present, the only other OSD activity investing BA 4 funds is the JNLWD, investing a small amount in the Active Denial System ACTD and in engine stopping technology.

Figure D-2 shows the OSD directed energy BA 1–3 investment. Although not explicitly shown in Figure 29, the fiscal year 2007 BA 1–3 directed energy investment is predominantly in laser technology with some $375 million compared to 45 million for HPM. The Air Force currently has the largest investment—approximately 25 percent of the total OSD directed energy investment. There is also a large portion of congressionally-directed investment (19 percent), as well as an investment in lasers by the High Energy Laser Joint Technology Office, discussed in further detail later in this section. For fiscal year 2007, the OSD portion includes $45 million from Special Operations Command for the Advanced Tactical Laser ACTD.

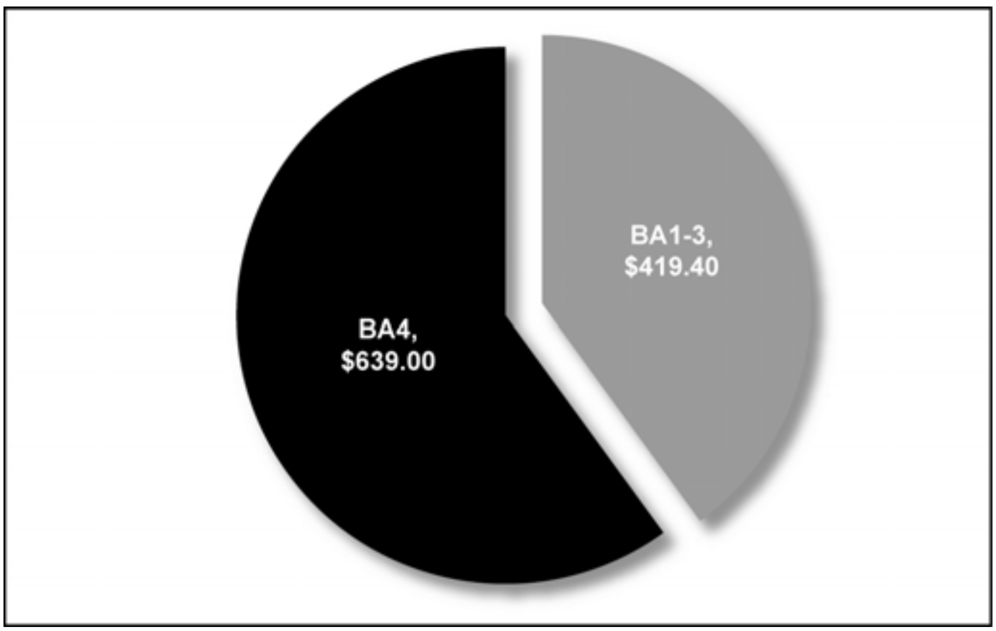

Figure D-1. OSD Directed Energy Budget Activity 1-4 Investment, Fiscal Year 2007 (millions of dollars)

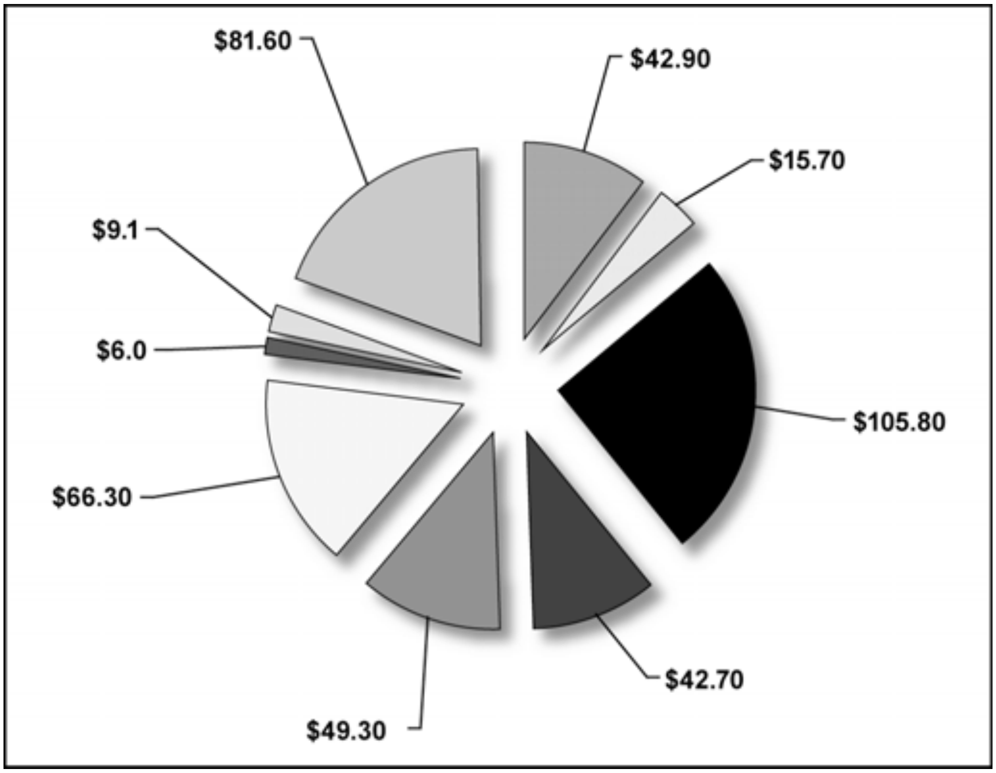

Figure D-2. OSD Directed Energy Budget Activity 1-3 Investment, Fiscal Year 2007 (millions of dollars)

Advanced Systems and Concepts Office

The Advanced Systems and Concepts (AS&C) office, which reports to DDR&E, is also involved in directed energy systems. AS&C is responsible for policies, plans and procedures, and guidelines for advanced concept technology demonstrations, now known as joint capabilities technology demonstrations (JCTDs). AS&C oversees evaluation of ACTD candidates and coordinates approval for those ACTDs selected for execution. In addition, AS&C oversees execution of ACTD programs to assess the military utility of proposed capabilities, and oversees planning and preparations for the transition of ACTDs into the formal acquisition process. Currently, there are two active directed energy ACTDs, the Active Denial System and the Advanced Tactical Laser. Both demonstrations are scheduled to complete at the end of fiscal year 2007. There is one directed energy program proposed for a fiscal year 2008 JCTD, Counter-Electronics High Power Microwave Advanced Munitions Project.

High Energy Laser Joint Technology Office

The High Energy Laser Joint Technology Office reports to the Deputy Under Secretary of Defense for Science and Technology, (DUSD [S&T]) located in the DDR&E office. This organization is relatively new, founded in 2000. The Fiscal Year 2000 Defense Authorization Act directed the Secretary of Defense to develop a unified plan for the Department of Defense to develop laser technology for potential weapons applications. This plan includes identification of potential weapons, identification of critical technologies and manufacturing capabilities required to achieve such weapons applications, a development path for those critical technologies and manufacturing capabilities, identification of the funding required in future fiscal years to carry out the laser master plan, identification of unfunded requirements in the laser master plan, and an appropriate management and oversight structure to carry out the laser master plan.

One of the recommendations of the resulting plan was the formation of the HEL-JTO to develop and manage a joint program for revitalizing HEL S&T and to serve as a clearinghouse for new S&T initiatives proposed by DOD components. The Fiscal Year 2001 Defense Authorization Act directed the Secretary of Defense to implement the management and organizational structure specified in that plan.

The HEL-JTO manages a portfolio of HEL technology development that flows into service and agency high energy laser weapons systems development and acquisition programs. In fiscal year 2004, USD (AT&L) directed transfer of the HEL-JTO program to the Air Force. The HEL-JTO budget lines moved to the Air Force, with unchanged service and agency participation in the HEL-JTO program. Oversight responsibility for the HEL-JTO program remains with the HEL Technology Council chaired by DUSD (S&T).

The deliverables from contracts awarded on behalf of the joint technology office are based on military department and service agency needs and are intended for transition to traditional acquisition programs. Some of these deliverables are to benefit the Missile Defense Agency Airborne Laser program, Army High Energy Laser Technology Demonstrator program, Navy Free Electron Laser program, and the Advanced Tactical Laser ACTD managed by U.S. Special Operations Command. In addition to work accomplished in the areas of lasers and beam control; the HEL-JTO has established tri-service Lethality and Modeling & Simulation Technical Area Working Groups. The specific project work is accomplished at DOD laboratories, industry, and academic institutions under the oversight of government subject matter experts. There are approximately 80 funded programs totaling about $65 million in fiscal year 2007.

One of the major initiatives supported by the HEL-JTO is developing a 100 kilowatt solid state laser, under the Joint High-Power Solid-State Laser project. This project, managed by the HEL-JTO and the military departments, offers the potential for the nation's first weapon's class tactical laser small enough to fit aboard combat aircraft, ground vehicles, and ships. Solid-state tactical lasers could be used for both offensive and defensive missions and offer the potential of being capable of generating enough laser energy to be an effective tactical weapon. Other initiatives include maritime propagation windows, the demonstration of a 25 kilowatt Free Electron Laser, at the appropriate wavelengths, and the demonstration of highly precise tracking algorithms at the Air Force North Oscura Peak site, and the High Energy Laser Test Facility at White Sands Missile Range.

Investments in HEL technologies are expected to transform warfighting, enabling revolutionary advances in engagement precision, lethality, speed of attack, and range, while minimizing collateral damage and complementing precision munitions capability. The HEL-JTO is proceeding in its mission to champion, communicate, and develop high energy laser technologies for use by DOD.

Joint Non-Lethal Weapons Directorate

The Joint Non-Lethal Weapons Directorate serves as the day to day management office for the Commandant of the Marine Corps in his role as the DOD Non-Lethal Weapons Executive Agent. The JNLWD conducts a wide range of activities that span across the Defense Department and beyond in its role as the central focal point for non-lethal weapons. These activities include sponsoring research into promising technologies that have potential application for non-lethal weapons. The JNLWD has provided emphasis on directed energy technology research for the next-generation of non-lethal weapons. The JNLWD has served as the primary resource sponsor and executing agent of the Active Denial System Advanced Concept Technology Demonstration and has invested in non-lethal directed energy technology research for both counter-personnel and counter-material applications. Current priorities include funding for directed energy vehicle and vessel stopping solutions.

Defense Advanced Research Projects Agency

The Defense Advanced Research Projects Agency, as a component of DDR&E, is the DOD-level central research and development organization. DARPA manages and directs selected basic and applied research and development projects, which are not only extremely high risk with respect to research and technology but also have a high payoff where success may provide dramatic advances for traditional military roles and missions. In this role, DARPA maintains the technological superiority of the U.S. military and prevents technological surprise from harming U.S. national security by sponsoring revolutionary, high-payoff research that bridges the gap between fundamental discoveries and their military use. For fiscal year 2007, DARPA is investing approximately $43 million in laser system research.

Missile Defense Agency

The Missile Defense Agency is tasked to develop and field an integrated Ballistic Missile Defense System capable of providing a layered defense for the homeland, deployed forces, friends, and allies against ballistic missiles of all ranges in all phases of flight. Using complementary interceptors, land-, sea-, air- and space-based sensors, and battle management command and control systems, the planned missile defense system will be able to engage all classes and ranges of ballistic missile threats. Missile defense systems being developed and tested by MDA are primarily based on hit-to-kill technology. It has been described as hitting a bullet with a bullet—a capability that has been successfully demonstrated in test after test. The Airborne Laser is MDA's primary boost-phase missile defense element, and is being developed to destroy ballistic missiles of all classes in their boost phase of flight using its megawatt-class high-energy laser.

Directed Energy Program Review Activity

The review process for directed energy programs has been extensive. The process includes:

- Reliance21 Directed Energy Technical Focus Team
- Defense Science Board Task Force on Directed Energy Systems and Technology Applications (plan to report June 2007)
- DUSD(S&T) High Power Microwave Steering Committee
- High Energy Laser Technology Council (oversees the High Energy Laser Joint Technology Office)
- DUSD(S&T) Technology Area Review & Assessment–Weapons, Team 3, Directed Energy
- Strategic Planning Guidance and directed energy net assessment
- The Joint IED Defeat Organization

Reliance 21 Directed Energy Technical Focus Team

Reliance 21, which is the replacement for the former Technology Area Review and Assessment S&T reviews, provides a framework to promote collaboration and cooperation between components to enhance the DOD S&T program. The new process utilizes technology focus teams to help integrate and coordinate strategic planning and investment strategies for the DOD S&T program.

Under the general guidance of the Defense S&T Advisory Group (DSTAG), technology focus teams closely examine select technology areas. For fiscal year 2007, one of six teams is the Directed Energy Technology Focus Team, which assists the DDR&E and the DSTAG by providing an assessment of the overall DOD S&T efforts in directed energy weapons technology. The team is chartered to:

- provide a succinct description of major work in this area by including DOD efforts, and, if relevant, other federal agency or related commercial work in the area and relating the technology work to capabilities identified by the Joint Staff or the services
- identify areas of effective cooperation and synergy, and, if applicable, activities that may be duplicative when the need is not clearly evident
- identify the responsibilities of each service or agency within this technology area and a lead service or agency designation as required
- recommend (if possible) future S&T efforts.

The technology focus team presents recommendations and findings to DDR&E and the DSTAG, as well as an associated roadmap documenting currently funded efforts and planned efforts from services and agencies.

DOD Test Community

The DOD test community has realized the need to prepare for the possibility of directed energy weapons testing in the future. The Strategic Planning Office in the Test Resource Management Center (TRMC), USD (AT&L), is responsible for this task. The center is involved in two specific S&T programs. One lies within the Test and Evaluation Science and Technology Program and the other within the Central Test and Evaluation Investment Program (CTEIP). Both programs have efforts supporting directed energy test and evaluation capabilities. The CTEIP program funds the Directed Energy Test and Evaluation Capability (DETEC) tri-service studies that have resulted in the prioritization and funding for directed energy test and evaluation capability S&T and technology development. The Phase 1 DETEC study was conducted in fiscal year 2003 and resulted in the development of five HEL test capabilities and seven HPM test capabilities. Phase 2 of the DETEC tri-service study is underway at this time and, at the end of fiscal year 2007, will report on prioritized needs for future test and evaluation S&T and CTEIP efforts.

National Intelligence Community

The National Intelligence Officer for Science and Technology should have a designated full-time intelligence officer responsible for producing information on foreign-directed energy programs. The person should be part of the mission manager effort to improve scientific and technical collection and serve as an advocate for improving the quality of collection against foreign-directed energy systems.

Directed Energy Security Classification

Each service has a component high-power microwave and high-energy laser OPR, responsible for determining classification levels for directed energy programs. For unresolved matters, issues are elevated to USD (AT&L) in the DDR&E organization and the Joint RF Coordination and Technical Interchange Group (in the case of HPM discrepancies) for final determination.

In general, basic research associated with HPM and HEL technology is considered unclassified, concept exploration may be at the collateral level, and weaponization efforts may be considered a special access program, once reviewed against the DOD special access program thresholds.

Effects testing results that describe and demonstrate lethality, vulnerability, and susceptibility to any system are classified at a collateral level. Possible countermeasures and counter-countermeasures are classified at the collateral level. Performance parameters (such as range and power), are classified at the collateral level when an individual parameter, or a combination of parameters, reveals lethality, vulnerability, susceptibility, capability, or possible weapon parameters. Weaponization component details may also be collateral secret. These examples are not all inclusive; refer to the HPM and HEL security classification guidelines for further details.

In the past, the OSD DDR&E HPM Steering Group and other panels, such as the Air Force Scientific Advisory Board and the OSD Technology Area Review & Assessment teams, have been concerned with the inconsistencies of separate component classification decisions and the general approach of over-classification of technology. This is currently being addressed by OSD and service components.

Appendix E. Glossary

ABL	Airborne Laser
ACTD	advanced concept technology development
ADS	Active Denial System
AF	Air Force
AFRL	Air Force Research Laboratory
AS&C	Advanced Systems and Concepts
ASD (NII)	Assistant Secretary of Defense for Networks and Information Integration
ATL	Advanced Tactical Laser
BA	budget activity
BMDS	Ballistic Missile Defense System
CC-COIL	closed-cycle COIL
CTEIP	Central Test and Evaluation Investment Program
COIL	chemical oxygen iodine laser
DARPA	Defense Advanced Research Projects Agency
DDR&E	Director, Defense Research and Engineering
DF	deuterium fluoride
DF-CO	deuterium fluoride-carbon dioxide
DETEC	Directed Energy Test and Evaluation Capability
DOD	Department of Defense
DPSS	diode-pumped solid-state
DSB	Defense Science Board
DSTAG	Defense S&T Advisory Group
DUSD (S&T)	Deputy Under Secretary of Defense for Science and Technology,
e-beam	electron beam
FEL	free-electron laser
GW	gigawatt

HEL	high- energy laser
HEL-JTO	High Energy Laser-Joint Technology Office
HF	hydrogen fluoride
HMMWV	High Mobility Multi-Wheeled Vehicle
HPM	high-power microwave
IEDs	improvised explosive devices
IFX	Integrated Flight Experiment
JCTDs	joint capabilities technology demonstrations
JHPSSL	Joint High Power Solid State Laser
JNLWL	Joint Non-Lethal Weapons Directorate
JTO	Joint Technical Office
MANPADS	man-portable air defense systems
MDA	Missile Defense Agency
MTHEL	Mobile Tactical High Energy Laser
OSD	Office of the Secretary of Defense
PC	personal computer
POM	program objective memorandum
RAM	rockets, artillery, and mortars
R&D	research and development
RF	radio frequency
S&T	science and technology
SBL	Space Based Laser
THEL	Tactical High Energy Laser
TRMC	Test Resource Management Center
UAV	unmanned aerial vehicles
USD (AT&L)	Under Secretary of Defense for Acquisition, Technology and Logistics
USD (I)	Under Secretary of Defense for Intelligence