

Directed Energy Weapons— Are We There Yet?

The Future of DEW Systems and Barriers to Success

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Introduction

In December 2007, the Defense Science Board (DSB) concluded directed energy weapons (DEW) research and development leading to the deployment of operational weapon systems had reached a near standstill. In a comprehensive report, the DSB task force observed, “after many years of development, there is not a single directed energy system fielded today, and fewer programs of record exist than in 2001.”¹ The DSB analysis concluded that while, “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.”

In March 2008, roughly one hundred representatives from the Office of the Secretary of Defense (OSD), The Department of Justice (DOJ), the Department of Energy (DOE), the military Services, DOD laboratories, private industry, and think tanks participated in a 2-day National Defense University (NDU) forum on “The Directed Energy Battlefield: Obstacles to Success” to engage in a frank examination of the status of DEW research. During that wide-ranging discussion, participants identified key challenges to the directed energy (DE) community and outlined a series of capability, credibility, and cultural gaps that obstructed the fielding of DEW systems.

The forum highlighted the concerns and recommendations of the DSB task force and shed light on continuing difficulties in fielding DEW systems. In fact, the issues go well beyond limitations in DEW concepts of operation and analysis of alternatives. The forum indicated that the principal barriers preventing the deployment of DEW devices lie in the following areas:

- Technology and engineering issues, including proof of concept, technology feasibility, system complexity, and lack of system weaponization (weight, size, reliability, maintainability, safety, operability).
- Reluctance of the military operational community to employ DEW (including non-lethal weapons) against personnel, although legal, treaty, and policy issues do not restrict their use.
- Overall DEW system costs, even absent less costly alternatives.
- Lack of an industrial business case to maintain industrial involvement.
- Lack of an operational case, including system limitations (such as all-weather capability and potential countermeasures).
- Perception issues, e.g., in the OSD office of the Director, Defense Research and Engineering (DDR&E) engendered by 40 years of DEW development without a fielded, high-power system.
- Lack of a senior Service/OSD champion to move technology to deployment.

The purpose of this paper is to examine the barriers to deployment listed above and suggest a strategy for an initial deployment that addresses these issues. This strategy will focus on current high-priority threats against which DEW would provide the best alternative for the military.

¹ “Defense Science Board Task Force on Directed Energy Weapons,” December 2007, available at <http://www.acq.osd.mil/dsb/reports/2007-12-Directed_Energy_Report.pdf>.

The utility of Directed Energy systems for military applications depends on several key considerations. The DEW concept must demonstrate the capabilities of an operational weapon system. The DEW concept must *not* require a significant logistics tail, a dedicated infrastructure, or highly skilled operators and maintenance crews. Over the short-term, these prescriptions imply the development of lower-power tactical applications, such as defense against swarming threats, man-portable air defense systems (MANPADS), sensor and electronics destruction/denial, and less-than-lethal antipersonnel applications, for which DEW devices have already demonstrated a potential capability.

This paper begins with a survey of DEW development and reviews how historical difficulties have prevented these systems from being deployed to the battlefield. The paper will then address current challenges and offers suggestions on a way ahead. The paper will *not* address the status of current programs, nor make suggestions for technology investment. These areas were well covered by the December 2007 DSB report on DEW.

History and Background

DOD funding of DEW technologies originated in the late 1960s. At that time, three distinct concepts were considered—high-energy lasers (HEL), high-power microwaves (HPM), and charged particle (electron) beams (CPB)²—with the objective of producing devices with enough power to “hard-kill” targets of interest, such as high-speed missiles.³ None of the first-generation DEW technologies survived as programs.

Three Paths for DEW Research

High-energy Lasers

The original High-energy Laser (HEL) program involved the Advanced Research Projects Agency (ARPA)⁴ and all the Services (the Marine Corps had an early program). The HEL was well funded and had high-level OSD interest. The original HEL concepts utilized carbon dioxide (CO₂) as the laser medium. The concepts of the gas dynamic laser (GDL) and the electric discharge laser (EDL) were developed and funded by industry. The Avco Corporation and the Hughes Research Laboratory were instrumental in early CO₂ HEL development; in time, almost all of aerospace industry developed laser programs. In addition, second- and third-tier companies (e.g., optical companies) developed expertise and programs.

Several DOD and National Laboratories also developed in-house research cadres. Early expectations were for a GDL weapon system prototype in the 1970s. Avco Corp. delivered a CO₂ GDL in the 100KW power range to each Service in 1971. The Tri-Service Laser (TSL) was supplied to the Army Research Laboratory in Huntsville, AL, the Naval Research Laboratory in Chesapeake Beach, MD, and the Air Force Research Laboratory in Albuquerque, NM.

Soon after the Army and Navy GDL lasers became operational at ground and sea level, a problem arose for their utility as a weapon that remains an issue for HELs: laser beam

² Electromagnetic launch weapons (e.g., rail guns) are sometimes considered to be DEW devices but are not included in this paper.

³³ *Hard kill* means physical destruction of the missile by a warhead or propellant kill or from an aerodynamic kill of the missile. Throughout this paper, expressions such as weapon-level power or ultra-high power imply the power to hard-kill such targets as cruise missiles or ballistic missiles.

⁴ In the early 1970s, “Defense” was added, so that ARPA became DARPA. Both terms are used in this paper, depending on the period in question.

propagation in “thick” (ground and sea level) air with aerosols and other particulate and molecular absorbers of electromagnetic energy. The CO₂ laser produces a beam with a wavelength of 10.6 μm, a wavelength with fairly low absorption in the atmosphere, but enough to cause a phenomenon called “thermal blooming” that was pronounced at powers well below that required for a high-power weapon. While straight absorption of the beam can be overcome by increasing beam power, thermal blooming cannot.

Thermal blooming is a non-linear effect that is exacerbated as power is increased. As the air in the beam path is heated by absorption of energy the index of refraction of the air changes, producing a “negative-lens” effect that spreads out the beam and reduces its intensity on the target. While a corrective technique known as “adaptive optics” has been developed to compensate for other optical distortions of the beam, it has not been effective for thermal blooming.

As the effects of thermal blooming were becoming manifest, ARPA was funding a new HEL concept called the deuterium fluoride (DF) chemical laser that operated with wavelengths from 3.6 to 3.98 μm, wavelengths with much less absorption than the CO₂ gas dynamic laser. At that time, in the early 1970s, the Navy discontinued work on CO₂ lasers and jointly funded, with ARPA, a demonstration DF chemical laser called the Navy ARPA Chemical Laser (NACL).

In the late 1970s, the Navy funded a weapon-level power demonstrator of the DF HEL called the Mid-Infrared Advanced Chemical Laser (MIRACL), with TRW as the principal laser developer and Hughes as the lead for the beam director. In 1983, Navy HEL funding was transferred to DARPA, but the Navy continued to manage the program at the Army’s White Sands test facility in New Mexico. In 1989, the MIRACL successfully engaged a crossing supersonic target, but a subsequent test against a closing target was unsuccessful.

Thermal blooming was still an issue, even for the DF chemical laser. Potential technological next steps, such as suppression of highly absorbing lines,⁵ were not funded, and Navy involvement with chemical lasers was concluded.

The Army also discontinued development of GDLs in the 1970s but continued research and development on EDLs and chemical lasers, looking for vehicle-mounted applications. By the 1980s, the Army had developed an operational, vehicle-mounted EDL sensor blinder in the Sting-Ray program, but the system was never fielded.

The Air Force, which was less concerned with propagation issues at high altitude, continued a GDL CO₂ demonstrator, the Airborne Laser Lab (ALL), over an 11-year experiment to prove that an HEL could be operated in an aircraft and employed against airborne targets. The laser, mounted in a modified KC-135 aircraft, destroyed Sidewinder missiles and a BQM-34A target drone in close-in engagements. While conducting these tests, the Air Force initiated development of the Chemical Oxygen-Iodine Laser (COIL), which is the technology employed in the weapon-scale Airborne Laser (ABL) program currently in development.⁶

⁵ DF lasers operate at wavelengths over a series of lines from 3.6 μm to 3.9 μm, some of which absorb more strongly than others.

⁶ For an early account of ABL development, see Hans Mark, *The Airborne Laser from Theory to Reality: An Insider’s Account*, Defense Horizons 12 (Washington, DC: National Defense University Press, April 2002).

High-power Microwaves

During the 1970s, all three Services developed High-power Microwaves (HPM) capability attuned to the constraints of their platforms and Service missions. Both HPM and CPB enjoyed robust funding. The Navy, with the largest platforms, investigated the potential of hard-kill HPM weapons.

The potential for hard-kill HPM was eventually discounted for several reasons, among them: plasma formation at the target caused by HPM-induced air breakdown shielded the target from the beam; HPM at weapon-level power could seriously disrupt commercial communications; and extremely large antennas would be required to focus the HPM beam. Because of these developments, HPM has become more of a high-powered electronic warfare tool aimed at destroying or disrupting sensors and electronics. Work continues in this arena for application against such threats as improvised explosive devices (IEDs).

Charged Particle Beams

The 1970s were also a period of major investment in charged particle beams by DARPA and the Navy. Of all the DEW concepts, CPB had the most assured ‘hard kill’ potential because energy would be distributed throughout the target (including the warhead and guidance system) rather than only at the surface. CPB, however, had major technological obstacles.

The technology to produce a very-high-current electron beam simply did not exist. Experts believed the program’s chances for success were relatively remote, and predicted the research would be fraught with serious technological difficulties.

For advocates, the fundamental challenge was creating a beam capable of retaining its power and direction while passing through the earth’s shifting, variable atmosphere. Typically, an electron beam with constant current and voltage quickly becomes unstable, creating beam breakup while propagating through the air. A potential solution to this problem involves complicated beam pulse shaping.

By the 1980s, although progress was being made, the high technological risk of solving these issues, coupled with cost and timeframe considerations, led to the termination of this effort.

Consolidation of DEW Programs

Major programmatic decisions, coupled with several failed or discontinued technology developments and demonstrations in the 1980s (such as the CPB program), had a profound impact on DEW development. The effects are still reflected in the current perceptions of DEW.

First, there was a Congressional desire to consolidate HEL programs in the services under a single manager, in particular DARPA. An even more significant impact on DEW resulted from the formation in 1984 of the Strategic Defense Initiative Organization (SDIO).

Most DEW funding was transferred from the services to SDIO, which instituted major DEW initiatives directed at strategic targets. These programs included: nuclear-pumped X-ray lasers (used to promote the program but quickly dropped as a viable technology); chemical lasers, with particular focus on hydrogen fluoride for space-based applications; free electron lasers (FELs); large-scale laser and mirror experiments; and hypervelocity rail guns.

In 1993, the SDIO was restructured as the Ballistic Missile Defense Organization (BMDO), with a mission focus shift from National missile defense to theater missile defense. This shift in

emphasis was accompanied by the cancellation of many DEW programs, leaving only chemical laser development for space-based applications and, subsequently, the ABL. While the Air Force remained significantly engaged in the ABL, Army and Navy technology investments in HEL had significantly fallen, along with Service interest.

A Decade of Declining Interest in DEW

By the late 1990s, the principal focus in HELs was in chemical lasers. Three major programs were in progress: the ABL and the Space-Based Laser, supported by BMDO and the Air Force, and the Theater High-energy Laser (THEL), funded by DDR&E and managed by the Army. The THEL was a joint program with Israel and successfully engaged rockets and artillery shells at its test bed. Funding for the next step, a mobile THEL (MTHEL), was not forthcoming, and the program halted. Currently, only the ABL is funded.

In technology development, the Air Force was the principal Service funder, focused on support for the ABL. The Army had initiated a modest effort in solid-state lasers (SSLs), motivated by a need for a compact laser that did not require toxic chemicals. The Navy, with Congressional funding, restarted FEL technology, predicated on the wavelength selectivity of an FEL to address the thermal blooming issue. Currently, the Navy is evaluating proposals to scale the FEL to 100KW, with the potential to further scale to higher-power levels, a program that would entail high cost and risk.⁷

By the end of the 1990s, Congress noted the significant decline in HEL technology development and provided legislation leading to the formation of the HEL Joint Technology Office (HEL-JTO) in June 2000. The charter of the HEL-JTO was to coordinate the Service HEL technology efforts and directly fund promising technology efforts in chemical, solid-state, and FEL lasers. The JTO has continued this mission from its office in Albuquerque, NM.

While there is no record of high-power HELs being fielded, from the 1970s on, lower-power lasers have increasingly been deployed on the battlefield, particularly for sensing, ranging, and targeting. Directed Infrared Countermeasure (DIRCM) lasers for blinding guidance systems of surface-to-air and air-to-air have been developed, and airborne counter-MANPAD systems have been fielded.

Current Developments

In addition to the THEL program managed by the Army, two other Advanced Concept Technology Demonstrations (ACTDs) were carried out by the Air Force in the 2000s: the Airborne Tactical Laser (ATL), and the Active Denial System (ADS). The ATL was a demonstration of a multi-kilowatt-sized COIL laser (the same technology as the ABL, but much less powerful) for tactical, ground-based targets. ATL is not currently a program of record. The ADS is a millimeter-wave, lower-power DEW device with the mission of non-lethal, antipersonnel control. This program will be discussed later in the discussion on impediments to fielding DEW systems.

⁷ The National Research Council, Board of Physics and Astronomy, *Scientific Assessment of High-Power Free-Electron Laser Technology*, January 2009.

At DARPA, development has focused on two potentially high-payoff SSL concepts. The first is centered on the development of 3kW fiber-laser amplifiers⁸ that can be coherently combined to the multi-100 kW level. Promised efficiencies can exceed 30 percent and lead to compact, high-power laser systems. Coherently combinable fiber-laser amplifier technology is currently at 150 watts. The second involves the coherent combining of laser diode arrays that could have even higher efficiencies, but face even more challenging scalability issues. DARPA is also addressing the beam director size and weight issue by developing an optical phased array⁹ similar in principle to a radar electronically steered array (ESA), but at one-ten-thousandth the wavelength. The coupling of the fiber-laser amplifiers to the optical phased array is a promising approach to a fieldable system.

A recent National Research Council (NRC) assessment for the Army¹⁰ that addressed the counter rocket, artillery, and mortar (RAM) mission with SSL technology found that the SSL technology readiness level for this mission was only at the proof-of-concept level. Furthermore, they estimated that fielding an operational weapon system at 400kW by 2018 could cost about \$470M, with high technological risk.

Summary of Progress: Unrealized Potential

While significant progress in DEW technology has been achieved over the past 40 years, most early expectations for fielding systems have not been achieved, and several major DEW programs have been abandoned without producing even a system demonstration. Funding and management decisions, such as the formation of the SDIO, have in the past marginalized Service roles and enthusiasm for putting up new funding. Operational and policy issues continue to delay deployment. A 2002 CTNSP paper¹¹ discussed HEL issues that are still valid, e.g., the operational and policy issues of space-based lasers as components of a highly automated weapon system in continuous orbit over friend and foe alike. Additional operational and policy issues have since arisen for lower-power, millimeter-wave, and laser systems, particularly for non-lethal applications.^{12,13}

On the positive side, new device technologies, such as solid-state lasers, fiber lasers, free-electron lasers, and millimeter-wave systems, have shown significant promise. Finally, new missions for which the attributes of DEW are appropriate, will expand the utility of DEW and lead to deployment, production, and renewed industry investment.

⁸Resolution in Fiber Lasers (RIFL), available at <<http://www.fiberopticsonline.com/article.mvc/DARPA-Awards-Northrop-Grumman-Contract-To-0001?VNETCOOKIE=NO>>.

⁹ Adaptive Photonic Phase Locked Elements (Apple); <http://www.darpa.mil/MTO/Programs/apple/index.html>.

¹⁰ The National Research Council, Committee on Directed Energy Technology for Countering Indirect Weapons, "Review of Directed Energy Technology for Countering Rockets, Artillery and Mortars (RAM)," ISBN:0-309-11172-2.

¹¹ Elihu Zimet, "High-Energy Lasers: Technical, Operational, and Policy Issues," Defense Horizons no. 18, October 2002.

¹² E.R. Bedard, "Nonlethal Capabilities: Realizing the Opportunities," Defense Horizons 9, March 2002.

¹³ Alec Wilkinson, "Non-Lethal Force," The New Yorker, pg. 26-33, June 2, 2008.

Military Utility

The threat scenarios that shaped the initial DEW programs were those of the Cold War. These threats included sophisticated Soviet weaponry employing stealth, speed, and hardening. Threats included advanced cruise missiles, ground-to-air and air-to-air missiles, ballistic missiles, and hardened ground vehicles. Hard kill of these threats typically requires an ultra-high-power laser beam applied for several seconds. These threats, and the technologies to defeat them, drove the HEL program throughout the Cold War and for some years beyond.

Emerging Missions for DEW Consideration

- Perform non-lethal engagements (e.g., crowd control)
- Attack vehicles, facilities, and personnel in an urban environment
- Defend infrastructure (e.g., power plants)
- Counter a range of enemy threats:
 - Mines and IEDs
 - vehicle-borne IEDs
 - suicide bombers
 - swarming small-boat threats to ships
 - rockets, artillery, and mortars
 - MANPADS
 - defend against enemy surveillance and lethal UAVs

In the 21st century, U.S. forces are likely to face a wider range of complex roles and missions. These will include low-tech threats from dispersed personnel, a scenario characterized by insurgent or terrorist groups. The battlefield for these threats is often urban, whether abroad or within the United States.

A list of emerging missions for which DEW might compare favorably with more conventional weapons systems includes several that utilize DEW systems with less power than traditional HEL systems, such as the ABL (see text box). As DEW technology proves its versatility, it seems likely that its adoption will lead to additional missions, and provide an impetus for the accelerated fielding of DEW across the board.

Obstacles to Success

The 2007 DSB task force report on DEW cited a June 2001 DSB report¹⁴ that noted “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.” The 2007 report observed that in the 6 intervening years between the two reports, disappointing lack of progress led to “a marked decline in interest on the part of operational customers, force providers, and industry.” This decline of interest has carried over to the office of the DDR&E, which is responsive to the operational community in prioritizing the S&T investment. The report states that:

- The ABL’s critical operational demonstration had slipped almost year for year since 2003.

¹⁴ Defense Science Board, “High Energy Laser Weapon Systems Applications,” June 2001.

- The space-based laser for missile defense had been effectively abandoned.
- The THEL program to provide battlefield capabilities for ground forces had been terminated.
- The Ground-Based Laser for Space Control was not being pursued.
- The THEL fighter was no longer a projected program.
- Future Combat Systems applications were no longer part of the FCS program.
- Laser blinding of guidance systems of air-to-air missiles has been demonstrated but not fielded.

Though the reason for each program's troubled history may be unique, the development of DEW systems share a common set of problems which have prevented research from progressing towards operational equipment. These barriers, as examined at the March 2008 DEW forum, are discussed below.

Science and Technology

Engineering Issues May be Insurmountable

The 1970s military missions for DEW were high-end, Cold War threats. DEW systems, in particular HEL systems, proposed to counter those threats led to requirements for ultra-high-power lasers. While ultra-high-power HELs have been achieved, notably in the DF MIRACL chemical laser in the 1980s, and more recently in the COIL chemical laser for the ABL, physics-based issues, technology maturity, and engineering issues have either terminated (MIRACL) or significantly delayed (ABL) their introduction.

With the exception of chemical lasers, other HEL concepts, such as solid-state lasers (SSL) and free-electron lasers (FEL) have only been scaled to 10s of kilowatts, with significant technology hurdles remaining to reach power levels needed for weapons. Ultimately, all technology must obey the laws of physics and be subjected to a proof of concept. The propagation of a beam in the atmosphere is determined by the properties of the atmosphere (absorption, refraction, and scattering).

While propagation may be optimized to some degree by wavelength selection and adaptive optics for beam correction, even an optimized beam may not retain enough power for all threat scenarios after atmospheric effects, such as thermal blooming. In addition, chemical lasers operate at wavelengths determined by the chemistry of their lasing process, fixing the wavelength for a given laser type (DF at 3.6 μm to 3.9 μm and COIL at 1.3 μm). SSLs operate at more favorable wavelengths for propagation (e.g., 1.06 μm , depending on the laser medium), and FELs can be designed to desired wavelengths and have some degree of wave-length tuning, limited by the coating on the optics. While there are proposed approaches to scale, both of these laser concepts to power levels suitable for weapons, significant physical risks remain that may not be tractable.

Physics-based issues also exist for HPM and CPB. For HPM, power levels are limited by air breakdown. If an HPM beam of very high power is focused to defeat an incoming target, the voltage levels in the focused beam create a plasma that shields the target from the beam. This limiting factor, along with other HPM engineering challenges (e.g., interference with commercial communications), has refocused HPM to lower-power applications, such as sensor and guidance

destruction, disruption, and denial. CPB also faces physics-based challenges, the most severe of which is “hose instability” in the propagating beam. Strong electric fields in the electron beam must be shaped to keep the beam stable. While approaches to shaping the beam profile were proposed, solutions remained long-term and high-risk. Other significant issues existed in developing a compact, high current and voltage electron accelerator for the beam generator. The need for such an accelerator, albeit with different specifications, is a current issue in scaling FELs to higher power.

DEW Programs are Risky and Expensive and require Long-term Investments

An issue related to proof of concept is that of *technological risks*, the time and money required to reach system prototype technology maturity. In terms of the DOD Technology Readiness Levels (TRLs): TRL 1-2 demonstrates that basic principles of physics are observed; TRL 3-4 relates to proof of concept in a breadboard laboratory environment; TRL 5-6 demonstrates component, system, or prototype in a relevant environment; TRL 7 relates to technical maturity in a system prototype demonstration in an operational environment; and TRL 8-9 is an actual system demonstration in mission level conditions. A system at TRL 7 needs to have addressed real battlefield conditions, including weather, dust, and countermeasures.

The place where many technologies fail to transition to actual weapons systems is in the so called “valley of death” from TRL 4 to TRL 7, where costs become too high for the technology community, but technology maturity is too low for the acquisition community. Historically, DARPA has played a major role in bridging the valley of death—often to find the Services unwilling to then fund the TRL 7-9 gap. Reacting to criticism for a deficiency of investments in fielded system, DARPA has moved to funding programs with shorter time frames and stronger transition potential. As mentioned earlier, DARPA’s DEW program now includes development stage, high-risk/high-payoff, fiber-based SSL technology and coherent phased-array beam combining and steering. Pressure on the military Services to transition technology from R&D to acquisition and deployment has typically been stronger than in DARPA, where speculative, highly technical programs can languish.

DEW programs are especially problematic because they can require 20 or more years and hundreds of millions of dollars to move from proof of concept to prototype. These programs require funding stability over long periods that encompass changes in leadership, priorities, and economic conditions. It is not surprising that programs like CPB, THEL, and the space-based laser have fallen by the wayside, even though they were showing technical advancement.

DEW Systems May Not Be Practical

In addition to the question, “Is the technology possible?” managers must consider whether the technology is also practical. Practicality implies that a new weapon system will be adapted to the needs of the battlefield in addition to demonstrating proof of concept (TRL 4) and a test bed demonstration in an operational environment (TRL 7). The THEL is an example of a program that showed excellent capability in a test bed, shooting down rockets and artillery shells, but was unable to secure funding to engineer the system for a mobile application (TRL 9). In fact, the engineering challenges in weaponizing THEL for a mobile system are formidable (and may require a different laser technology than a chemical laser, such as a fiber-based SSL).

In general, high-power DEW systems are large and heavy, highly complex, and sensitive to shock and vibration. These characteristics do not endear them to warfighters. The ABL is the only high-power DEW weapon system funded (by the Missile Defense Agency (MDA)) to

achieve TRL 7 status and go on to actual test demonstration. As the DSB pointed out, however, the program's critical operational demonstration has slipped almost year for year since 2003. The reason for the delay is largely due to the system's cumbersome size and weight. Over the past decade, much of the hope for fielding of a DEW has rested on the chemical laser ABL, which had been well funded and had high priority in the MDA. But as the program has encountered repeated delays, enthusiasm about DEW has again turned to uncertainty.

Alternative HEL concepts to chemical lasers are being actively pursued by the Services and the HEL-JTO. In particular, SSLs (including fiber-laser amplifiers coherently combinable into optical phased arrays) and FELs that address shortcomings in chemical lasers, but also will present unique engineering challenges if these systems are to be weaponized (assuming the technology permits scale-up to weapon size). Slab-based SSLs have a particular problem in removal of waste heat, unlike chemical and FELs. Technology and engineering solutions are still being developed. For example, the large surface area-to-volume ratio of a fiber compared to a SSL slab provides a better geometry for cooling. FELs have a particular requirement for shock and vibration isolation due to the requirement for very fine alignment of the high-current and high-voltage electron beam. FELs also require high vacuum and cryogenic cooling.

As a final engineering consideration, fielded DEW systems raise concerns about the so-called "ilities"; reliability, maintainability and operability. In general, high-power DEW systems tend to be large, complex, and sensitive to shock and vibration. In addition, the complexity of many DEW systems requires highly skilled operators and maintenance crews to keep the systems operational. All of these engineering considerations mitigate against decisions to deploy DEW on the battlefield.

Public Perception

The preceding section on technology and engineering issues indicate that most ultra-high-power DEW weapons systems are not yet ready for production. For several lower-power DEW concepts, technology is mature, but the military is still reluctant to employ weapons that may be perceived as inhumane.

The development of DEW for antipersonnel use, including non-lethal weapons, has been an area of research traditionally surrounded by public skepticism, fear, and distrust. Part of the problem of perception has been based on weapons designed, as some have imagined, to set targets alight, sterilize personnel, or blind subjects en masse. Such misinformation often feeds public fears domestically and incites conspiratorial rumors abroad that risk damaging the reputation of the United States as a forthright international actor. Nevertheless, the claims serve as a persistent warning to policymakers and DEW advocates.

Considerable discussion occurred during the March 2008 DEW forum at NDU about the Active Denial System (ADS), a millimeter-wave, non-lethal weapon system that produces a burning sensation in the skin but, properly used, does not penetrate to tissues beneath or cause burns. The ADS was considered by many in the forum as a stalking horse for the introduction of DEW to the battle field.

A recent WIRED blog Network release¹⁵ entitled "Army Orders Pain Ray Trucks; New Report Shows 'Potential for Death'" illustrates the public relations issue associated with the introduction

¹⁵ David Hambling, Wired Blog Network, Army Orders Pain Ray Trucks; New Report Shows "Potential for Death," available at <<http://blog.wired.com/defense/2008/10/army-ordering-p.html>>.

of this system. In fact, the “new report”¹⁶ referenced in the Wired report points out that the ADS provides the technical possibility of producing second- and third-degree burns. However, the ADS program states that second and third-degree burns are possible only under the most dire of circumstances. These are legitimate concerns that the program needs to address. However, as the Wired article adds in closing, “this potential hazard need not be a show-stopper—existing less-lethals, such as plastic bullets and tear gas, can also be fatal in some circumstances.” Perception issues for ADS include visions of its use on American citizens for crowd control, misuse as an instrument of torture, severe burning, and even sterilization.

Legal Uncertainties

While DOD policy and international treaties prohibit the deployment of weapons specifically designed to cause blindness, no policy, treaties, or laws prohibit the deployment of non-lethal DEW weapons, even if eye damage could result as an unintended consequence.

During the NDU forum, several speakers argued that international trends in R&D indicate the U.S. could quickly fall behind other states attempting to operationalize DE technology, particularly in the area of antipersonnel weapons. This development would deny American forces the ability to dominate key disruptive technologies and risks placing in jeopardy a whole generation of underequipped U.S. warfighters. According to one legal expert, “The lesson is that if you come up with something new, you will face allegations of illegality while others quietly develop the same programs.”

System Costs

In this paper, a distinction has been made between high- and lower-power DEW systems. High-power and low-power DEW systems are only being compared here relative to the issue of introducing them to the battlefield. Comparisons of military applications and utility are generally meaningless, because they usually address completely different missions. Distinctions reside in different technology risk and in different development and life-cycle costs.

Because no high-power DEW system has been fielded, life-cycle costs have not been determined. However, the most advanced DEW system, the ABL, provides estimates as to potential HEL costs. DEW systems deliver energy to a target at the speed of light. For missions involving very small engagement-time windows, such as destroying ballistic missiles in their boost phase, an airborne HEL was the only technology available to meet these timelines when the ABL program was initiated in 1994¹⁷. Program funding for the ABL through FY2008 has been \$4.8B; current yearly expenditures are about \$500M. Life-cycle costs for fielded systems are estimated to exceed \$1B per ABL system.

While these development costs are high, they are not much higher than the development costs of other MDA missile systems for mid-phase and terminal defense. However, while the MDA currently has a high priority in DOD R&D, it is unlikely that the Services would attempt to undertake such expensive programs on their own under current fiscal constraints, even if such

¹⁶ Jürgen Altmann, “Millimeter Waves, Lasers, Acoustics for Non-Lethal weapons? Physics, Analyses, and Inferences,” DSF-Forschung, available at <<http://www.bundesstiftung-friedensforschung.de/pdf-docs/berichtaltmann2.pdf>>.

¹⁷ Since 1994, advanced hypervelocity ship- and UAV-launched kinetic kill weapons have been also considered for boost-phase kill. Bolkcom and Hildreth, CRS Report for Congress, *Airborne Laser (ABL) Issues for Congress*, July 9, 2007.

programs provided enhanced capability. Also, as mentioned above, the NRC study on SSL for the RAM mission had a projected 10 year development cost of \$470M. It remains to be seen if the Army takes this technology out of the technology base and into production. Development by the Navy of a weapons power level FEL for shipboard defense may expect similar technology and financial struggles.

By way of cost comparison, lower-power DEW systems, such as the ADS millimeter-wave, non-lethal weapon, have acquisition costs in the millions of dollars rather than the hundreds of millions for proposed HEL hard-kill weapon systems. Looking only at the issue of affordability, considerably more obstacles stand in the way of high-power HEL procurement than lower-power systems. These obstacles can be overcome only by a high-priority need, such as the ABL, a concept of operations as the basis for decisions relating to technical, employment, policy planning, and priorities,¹⁸ and an analysis of alternative approaches to filling the gap.

Poor Business Plan

Industrial involvement in DEW goes back to the origins of the program in the late 1960s, when industry developed the fundamental technology. The early enthusiasm for DEW drew many top scientists and engineers into the DEW community. By the mid 1970s, most of the aerospace companies and many second- and third-tier companies were engaged in DEW development. Two significant constraints, starting in the 1990s, have diminished this world-class industrial base.

The first was the general consolidation of the aerospace industry following the end of the Cold War. Major early DEW developers, such as Avco, TRW, Hughes and Rocketdyne, have been absorbed into the few remaining aerospace companies, such as Boeing, Northrop Grumman, Lockheed, and Raytheon, where DEW competes for resources. Other smaller companies have vanished or gone out of the DEW business. This has tended to limit the competition of new ideas and technologies.

Another constraint relates to the lack of the Services fielding DEW systems. Industry derives most of its profits from the production of fielded systems rather than from R&D. Without a business case to pursue DEW technology, industrial interest has waned. DEW enthusiasts within industry have had an increasingly difficult time convincing their management to continue DEW R&D in light of the poor track record for transition.

Incomplete Operational Assessments

The first two bottom line findings of the DSB 2007 DEW task force study deal directly with the issue of needing an operational case for DEW employment. The task force recommended that “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.” In addition, “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.”

System CONOPS¹⁹ and analysis of alternatives (AOA) are essential for all acquisition programs, not just DEW systems. However, CONOPS and AOAs for DEW systems include issues derived from the particular capabilities and limitations of each DEW concept. The propagation of infrared and millimeter-wave energy is affected by atmospheric conditions: heavy rain, fog, dust,

¹⁸ DSB 2007, *ibid*.

¹⁹ CONOPS is short for Concept of Operations.

and smoke can severely limit DEW effectiveness, particularly at ground and sea levels. The impact of some countermeasures to some DEW systems²⁰ have been addressed, but in the absence of operational experience in the battlefield, the robustness of DEW systems to countermeasures remains an open question.

A further concern relates to the operation of DEW in concert with other weapon systems. For example, the Navy has examined HEL weapons for ship-based, cruise missile defense. The HEL has shown effectiveness against high-speed, highly-maneuvering cruise missiles, but thermal blooming has limited its effectiveness in head-on engagements, where anti-missile systems, such as the Rolling Airframe Missile and the Standard Missile, are most effective. CONOPS and AOAs for ship missile defense need to address these systems collectively rather than separately. If a DEW system is to be a stand-alone weapon, then all its potential shortcomings must be addressed to the satisfaction of the operational community. In general, this level of confidence has not been achieved.

No Senior DOD Champion

Senior DOD acquisition officials are faced with difficult funding choices in the coming years due to: a constrained budget climate in an economic downturn; cost overruns on existing programs; the operational costs in Iraq, Afghanistan, and elsewhere; fixed costs to support troops, veterans, and infrastructure; and the costs of replacing military inventory expended in war. Additional choices derive from alternative warfighting scenarios covering “conventional” warfare against a peer competitor and the irregular war against insurgents and terrorists we are engaged in today. The tactics and equipment to pursue these alternative forms of warfare are often incongruent.

Negative perception issues about DEW have evolved based on the obstacles to success described in the sections above coupled with the historical lack of deployment over the past 40 years. While various DEW systems have had strong senior leadership support in the past, DDR&E participation in the March 2008 DEW forum at NDU indicated a current cautious approach. Senior leadership in the Services and DOD Agencies voice some support for DEW R&D, but remain skeptical about an operational deployment plan.

²⁰ Countermeasures include hardening, reflective coatings, spinning to prevent spot heating, obscurants to absorb radiation, decoys and counter-attack on the DEW system.

Conclusion and Recommendations for a Way Ahead

The title of this paper poses the question “are we there yet?” relative to fielding DEW. The simple answer to this question is, “No.” While directed energy, in terms of low-power lasers and millimeter-wave devices, have become ubiquitous on the battlefield for communications, detection, imaging, targeting, range-finding, and electronic warfare, the potential for using high-power DEWs in the field remains unrealized. This paper has described the broad challenges which continue to delay DEW deployment, but has also shown that the principal obstacles fundamentally differ for each system.

Two DEW systems that appear to be closest to deployment at this time are the ABL and the ADS; different systems with very separate challenges. The principal obstacles to deploying ABL relate to engineering problems and potential life-cycle costs. The ABL does not have perception problems in terms of mission or antipersonnel implications. By contrast, ADS suffers from significant perception issues but has produced a fieldable prototype. Both systems now enjoy industrial support, but the cancellation of either program could send a broadly negative message about the feasibility of DEW, across the board.

DEW advocates struggle with obstinate uncertainties that undermine their effectiveness. Cultural gaps reinforce widespread misperceptions about the purpose, operational limits, and legal restrictions related to non-lethal DEW. Credibility issues surround high-power DEW programs, which may have been “overhyped” in the past and seem to lack a realistic investment strategy for the future. Finally, knowledge about the operational effectiveness of some proposed DEW devices is scarce, and operators, policymakers, and defense contractors are wary of supporting programs that remain experimental.

During the NDU DEW forum, attendees struggled with recommendations for a “way ahead.” Attendees agreed that one of the principal obstacles to fielding DEW was the lack of high-level interest due to a history of unfulfilled technological promises. However, U.S. operations in Iraq and recent transformations in the military have changed the center of gravity for the potential utility of DEW. Commanders have largely begun de-emphasizing the importance of high-power weapons to destroy enemy weapon platforms. They emphasize, instead, a need for lower-power applications, such as sensor and electronics destruction/denial and less-than-lethal antipersonnel applications. Forum participants suggested that to keep enthusiasm for DEW programs alive, DDRE should redirect its efforts to lower-power systems that have potential for shorter-term results. The termination of many high-profile programs during the past 5 years had come as a shock to many in the DE community. There was a general perception among attendees that DOD needs to move from DE research to fielding real-world applications that build a library of operational experience.

Participants also agreed that, among the technologies considered during the forum, the ADS appeared to have the potential to shatter cultural barriers that have stigmatized DE as “death-ray” technology. Deemed safe and effective in extensive preliminary testing, with a scalable level of intensity, and possessing a range exceeding that of non-lethal alternatives, ADS is capable of altering public perceptions about the use of DEW against human targets. Also, ADS has exhibited a number of operational advantages not shared by larger, more exotic DE systems: portability, a light logistics train, relative simplicity, and the ability to be mounted on standard platforms, such as trucks.

The audience was optimistic that ADS technology would follow the cultural template of other non-lethal devices that had gained widespread social acceptance after initial resistance. A prominent example was Taser® technology, which was introduced to law enforcement over a decade ago. A Taser representative explained that Taser's widespread adoption was the result of a marketing strategy that employed:

- A public education campaign, including high-level endorsements from subject experts advertising the product's limits and uses, combined with a customer relations team that addresses claims about the equipment's perceived deficiencies.
- A training regime that emphasized safety and transparency.
- Exhaustive scientific testing that compared results against alternative systems in a realistic, measurable fashion.
- Targeted demonstrations that introduced the product to commanders and operators.

The ethical and legal implications of DEW technology, unlike the Taser, remain largely undefined. There exists a misperception among mid-level policy officials that DEW systems risk violating international treaties and domestic laws. Several participants suggested these fears could be alleviated by involving attorneys early in the requisition process. Others argued that DEW devices might be designed to accommodate legal considerations, e.g., by creating options for "dialed" intensity level, focus, or beam visibility.

While attendees at the NDU forum nearly unanimously supported the ADS, there was less agreement on the way ahead for other DEW systems. Some attendees argued that policymakers would only embrace DEW after being presented with a complete, deployable weapon system. Once the benefits of DEW devices were demonstrated, these participants argued, operators would begin demanding the new technology. Other attendees disagreed with what they called a "build it and they will come" approach. They preferred a more focused approach, and urged development of non-lethal DEW programs to fill U.S. capability gaps to support counterinsurgency warfare and complex operations, e.g., stopping or disabling a moving vehicle, and dissuading or immobilizing individuals.

New weapon systems that have a significant impact on operations require both fieldable prototypes and a CONOPS, as called for by the DSB DEW Task Force. The Predator UAV provides a parallel programmatic example. The Predator initially lacked Service support but became a major warfare tool after the development of a fieldable prototype as an ACTD and the development of operational concepts for surveillance and attack. While both the THEL and ATL have had successful test-bed demonstrations as ACTDs, neither has developed a fieldable prototype, and their CONOPS are relatively undefined, particularly for the ATL, due to limited knowledge of system capability.

The experiences of the Services and DARPA with the development of high-power HEL systems, in which program risk and cost were underestimated, indicate that a cautious approach should be taken to scale-up of SSL and FEL, the lasers of choice for future Service missions. While it is important to continue development of these technologies because of their high military potential, significant technical hurdles must be overcome to reach power levels of even 100s of KW, which are far short of what is needed for weapons. Higher power levels are even more challenging, and breakthroughs will be required along the way. These programs will take considerable time to

reach full potential, so lower-power applications should be considered along the development path (see table 1 for examples of such applications).

The NDU Forum yielded two key recommendations for overcoming the obstacles to success in fielding first-generation DEW systems:

- The DEW S&T community must work to overcome the perception of its unproductive legacy. To do so, the community needs to field systems that will help demystify the new technology. Lower-power systems to defeat soft targets, such as light vehicles and UAVs, to counter sensors, and to produce non-lethal effects are suitable for early operational evaluation should be given high priority.
- A coordinated, dedicated, and long-term strategic communications plan is needed to facilitate the introduction of DEW, in particular for non-lethal DEW, such as the ADS.

The expectation is that success will breed success, thus overcoming disillusionment with DEW. In this new environment, a senior DOD champion could emerge to promote development and deployment of DEW.