



Navy Shipboard Lasers for Surface, Air, and Missile Defense: Background and Issues for Congress

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Summary

Department of Defense (DOD) development work on high-energy military lasers, which has been underway for decades, has reached the point where lasers capable of countering certain surface and air targets at ranges of about a mile could be made ready for installation on Navy surface ships over the next few years. More powerful shipboard lasers, which could become ready for installation in subsequent years, could provide Navy surface ships with an ability to counter a wider range of surface and air targets at ranges of up to about 10 miles. These more powerful lasers might, among other things, provide Navy surface ships with a terminal-defense capability against certain ballistic missiles, including China's new anti-ship ballistic missile (ASBM).

The Navy and DOD have conducted development work on three principal types of lasers for potential use on Navy surface ships—fiber solid state lasers (SSLs), slab SSLs, and free electron lasers (FELs). One fiber SSL prototype demonstrator developed by the Navy is the Laser Weapon System (LaWS); another Navy fiber SSL effort is called the Tactical Laser System (TLS). Among DOD's multiple efforts to develop slab SSLs for military use was the Maritime Laser Demonstration (MLD), a prototype laser weapon developed as a rapid demonstration project. The Navy has developed a lower-power FEL prototype and is now developing a prototype with scaled-up power. These lasers differ in terms of their relative merits as potential shipboard weapons.

Although the Navy is developing laser technologies and prototypes of potential shipboard lasers, and has a generalized vision for shipboard lasers, the Navy currently does not have a program of record for procuring a production version of a shipboard laser, or a roadmap that calls for installing lasers on specific surface ships by specific dates. The possibility of equipping Navy surface ships with lasers in coming years raises a number of potential issues for Congress, including the following:

- whether the Navy should act now to adopt a program of record for procuring a production version of a shipboard laser, and/or a roadmap that calls for installing lasers on specific surface ships by specific dates;
- how many types of lasers to continue developing, particularly given constraints on Navy funding, and the relative merits of types currently being developed; and
- the potential implications of shipboard lasers for the design and acquisition of Navy ships, including the Flight III DDG-51 destroyer that the Navy wants to begin procuring in FY2016.

In addition to decisions on whether or not to fund continued development of potential shipboard lasers, options for Congress regarding potential shipboard lasers include, among other things, encouraging or directing the Navy or some other DOD organization to perform an analysis of alternatives (AOA) comparing the cost-effectiveness of lasers and traditional kinetic weapons (such as missiles and guns) for countering surface, air, and missile targets, and encouraging or directing the Navy to adopt a program of record for procuring a production version of a shipboard laser, and/or a roadmap that calls for installing lasers on specific surface ships by specific dates.

Contents

Introduction.....	1
Issue for Congress	1
Scope, Sources, and Terminology	2
Background.....	3
Shipboard Lasers in General.....	3
Potential Advantages and Limitations of Shipboard Lasers.....	3
Potential Targets for Shipboard Lasers.....	7
Required Laser Power Levels for Countering Targets	7
Types of Lasers Being Developed for Potential Shipboard Use.....	8
Fiber Solid State Lasers (Fiber SSLs)	9
Slab Solid State Lasers (Slab SSLs).....	11
Free Electron Lasers (FELs)	12
Navy Surface Fleet’s Generalized Vision for Shipboard Lasers.....	13
Remaining Technical Challenges	14
ONR Solid-State Laser Technology Maturation Effort	15
Naval Directed Energy Steering Group.....	16
Directed Energy Vision for U.S. Naval Forces.....	18
Destroyers and LCSs Reportedly Leading Candidate Platforms.....	19
FY2014 Funding Request.....	19
Issues for Congress.....	22
Program of Record and Roadmap	22
Arguments Against Developing a Roadmap or Program of Record	23
Arguments Supporting Developing a Roadmap or Program of Record.....	24
Number of Laser Types to Continue Developing	28
Potential Strategies.....	28
Relative Merits of Laser Types.....	28
Implications for Ship Design and Acquisition.....	30
Options for Congress	32
Legislative Activity for FY2014	33
FY2014 Funding Request.....	33
FY2014 National Defense Authorization Act (H.R. 1960/S. 1197)	33
House.....	33
Senate	35
FY2014 DOD Appropriations Act (H.R. 2397).....	36
House.....	36

Figures

Figure C-1. Photograph of LaWS Prototype	42
Figure C-2. Rendering of LaWS Integrated on CIWS Mount	43
Figure D-1. Rendering of TLS Integrated on Mk 38 Machine Gun Mount.....	45
Figure E-1. Photograph of MLD on Trailer	49
Figure E-2. Schematic of MLD	49

Figure E-3. Rendering of MLD in Notional Shipboard Installation 50
Figure F-1. Photograph of an FEL Facility..... 53
Figure F-2. Simplified Diagram of How an FEL Works..... 54
Figure F-3. Schematic of an FEL..... 54

Tables

Table 1. Surface Navy’s Generalized Vision for Shipboard High-Energy Lasers 14
Table A-1. Approximate Laser Power Levels Needed to Affect Certain Targets..... 37

Appendixes

Appendix A. Laser Power Levels Required to Counter Targets 37
Appendix B. Navy Organizations Involved in Developing Lasers..... 39
Appendix C. Additional Information on Laser Weapon System (LaWS)..... 40
Appendix D. Additional Information on Tactical Laser System (TLS)..... 44
Appendix E. Additional Information on Maritime Laser Demonstration (MLD) 46
Appendix F. Additional Information on Free Electron Laser (FEL)..... 51
Appendix G. Innovative Naval Prototypes (INPs)..... 55
Appendix H. DOD Technology Readiness Levels (TRLs)..... 56
Appendix I. Protocol on Blinding Lasers 57
Appendix J. Illumination of Objects in Space 60
Appendix K. Section 220 of FY2000 Defense Authorization Act (P.L. 106-398)..... 61

Contacts

Author Contact Information..... 63

Introduction

Issue for Congress

Department of Defense (DOD) development work on high-energy military lasers, which has been underway for decades, has reached the point where lasers capable of countering certain surface and air targets at ranges of about a mile could be made ready for installation on Navy surface ships over the next few years. More powerful shipboard lasers, which could become ready for installation in subsequent years, could provide Navy surface ships with an ability to counter a wider range of surface and air targets at ranges of up to about 10 miles. These more powerful lasers might, among other things, provide Navy surface ships with a terminal-defense capability against certain ballistic missiles, including China's new anti-ship ballistic missile (ASBM).¹

In October 2012, the Chief of Naval Research, Rear Admiral Matthew L. Klunder, reportedly stated that he expects directed-energy weapons to be installed and integrated into ship combat systems within the next two years.² On April 8, 2013, the Navy announced that it would install a prototype solid state laser called the Laser Weapon System (LaWS) on a ship stationed in the Persian Gulf in early 2014 to conduct continued evaluation of shipboard lasers in an operational setting.³

Compared to existing ship self-defense systems, such as missiles and guns, lasers could provide Navy surface ships with a more cost effective means of countering certain surface, air, and ballistic missile targets. Ships equipped with a combination of lasers and existing self-defense systems might be able to defend themselves more effectively against a range of such targets. Equipping Navy surface ships with lasers could lead to changes in naval tactics, ship design, and procurement plans for ship-based weapons, bringing about a technological shift for the Navy—a “game changer”—comparable to the advent of shipboard missiles in the 1950s.

Although the Navy is developing laser technologies and prototypes of potential shipboard lasers, and has a generalized vision for shipboard lasers, the Navy currently does not have a program of record⁴ for procuring a production version of a shipboard laser, or a roadmap that calls for installing lasers on specific surface ships by specific dates.

¹ For more on China's ASBM development effort, see CRS Report RL33153, *China Naval Modernization: Implications for U.S. Navy Capabilities—Background and Issues for Congress*, by Ronald O'Rourke.

² Megan Eckstein, “Official: Laser Weapons Ready For Shipboard Integration Within Two Years,” *Inside the Navy*, October 29, 2012.

³ “Navy Leaders Announce Plans for Deploying Cost-Saving Laser Technology,” *Navy News Service*, April 8, 2013; Thom Shanker, “Navy Deploying Laser Weapon Prototype Near Iran,” *New York Times*, April 9, 2013: 4; Mike McCarthy, “Navy Deploying Laser For Taking Out Drones,” *Defense Daily*, April 9, 2013; Graham Warwick, “U.S. Navy Planning Gulf Deployment For Laser Weapon,” *Aerospace Daily & Defense Report*, April 9, 2013: 6; Megan Eckstein, “Navy-Built Laser Weapon System Will Begin Demo On Ponce In Early 2014,” *Inside the Navy*, April 15, 2013;

⁴ A program of record, or POR, is a term sometimes used by DOD officials that means, in general, a program in the Future Years Defense Plan (FYDP) that is intended to provide a new, improved, or continuing materiel, weapon, or information system or service capability in response to an approved need. The term is sometimes used to refer to a program in a service's budget for procuring and deploying an operational weapon system, as opposed to a research and development effort that might or might not eventually lead to procurement and deployment of an operational weapon system. If a research and development effort is converted into a program or record for procuring an operational weapon system. (continued...)

The central issue for Congress is whether to approve or modify the Administration's proposed funding levels for development of potential shipboard lasers, and whether to provide the Navy or DOD with direction concerning development and procurement programs for shipboard lasers. Potential specific issues for Congress include the following:

- whether the Navy should act now to adopt a program of record for procuring a production version of a shipboard laser, and/or a roadmap that calls for installing lasers on specific surface ships by specific dates;
- how many types of lasers to continue developing, particularly given constraints on Navy funding, and the relative merits of types currently being developed; and
- the potential implications of shipboard lasers for the design and acquisition of Navy ships, including the Flight III DDG-51 destroyer that the Navy wants to begin procuring in FY2016.

Decisions that Congress makes regarding potential shipboard lasers could significantly affect future Navy capabilities and funding requirements, the U.S. industrial base for military lasers, and the industrial base for existing shipboard self-defense systems.

Scope, Sources, and Terminology

This report focuses on potential Navy shipboard lasers for countering surface, air, and ballistic missile threats. It does not discuss the use of lasers on Navy aircraft or submarines, or the use of lasers by other military services.

This report is based on unclassified information from Navy, RAND,⁵ industry briefings on shipboard lasers provided to CRS and the Congressional Budget Office (CBO) in the summer of 2010, a follow-on unclassified Navy briefing on shipboard lasers provided to CRS and CBO in May 2011, and unclassified open-domain information. CRS requested the Navy and industry briefings to support the preparation of this report. Unless otherwise indicated, information presented in this report (including the appendices) is taken from the briefings.

For purposes of this report, the term "short range" generally refers to ranges of one or two nautical miles, while references to longer ranges or extended ranges refer to ranges of up to about 10 nautical miles.⁶ Lasers are one type of directed energy weapon (DEW); other DEWs include microwave weapons and millimeter wave weapons.

(...continued)

system, the program might then be conducted under the DOD's process for managing the acquisition of weapon systems, which is discussed further in CRS Report RL34026, *Defense Acquisitions: How DOD Acquires Weapon Systems and Recent Efforts to Reform the Process*, by Moshe Schwartz.

⁵ The RAND briefing was based on an evaluation of directed energy technologies that RAND performed for the Navy. At the Navy's direction, RAND collaborated on the study with the Center for Naval Analysis (CNA) and the MITRE Corporation.

⁶ In discussions of other types of defense systems, the terms short range and long range could have considerably different meanings. In discussions of the ranges of military airplanes or ballistic missiles, for example, the term short range might mean a range of hundreds of miles, while references to longer ranges could refer to ranges of thousands of miles.

Background

Shipboard Lasers in General

Potential Advantages and Limitations of Shipboard Lasers

Lasers are of interest to the Navy and other observers as potential shipboard weapons because they have certain potential advantages for countering some types of surface, air, and ballistic missile targets. Shipboard lasers also have potential limitations for countering such targets. Potential advantages and limitations are discussed below.

Advantages

Potential advantages of shipboard lasers for countering surface, air, and ballistic missile targets include the following:

- **Low marginal cost per shot.** Shipboard lasers could counter surface, air, and ballistic missile targets at a low marginal cost per shot. The shipboard fuel needed to generate the electricity for firing an electrically powered laser would cost less than a dollar per shot (some sources express the cost in pennies per shot).⁷ In contrast, the Navy's short-range air-defense interceptor missiles cost roughly \$1.0 million to \$1.4 million each, and its longer-range air- and missile-defense interceptor missiles cost several million dollars each.⁸ A laser can give a ship an alternative to using an expensive interceptor missile to achieve a "hard kill"⁹ against a much less expensive target, such as an unsophisticated unmanned air vehicle (UAV). A low marginal cost per shot could permit the Navy to dramatically improve the cost exchange ratio—the cost of the attacker's weapon compared to the Navy's marginal cost per shot for countering that weapon. Cost exchange ratios currently often favor the attacker, sometimes very significantly. Converting unfavorable cost exchange ratios into favorable ones could be critical for the Navy's ability in coming years to mount an affordable defense against adversaries that choose to deploy large numbers of small boats, UAVs, anti-ship cruise missiles (ASCMs), and ASBMs for possible use against U.S. Navy ships.

⁷ See, for example, Geoff Fein, "Navy Leveraging Commercial Lasers To Shoot Down UAVs," *Defense Daily*, May 11, 2010: 3-4.

⁸ The Navy's short-range shipboard interceptor missiles include Rolling Airframe Missiles (RAMs), which currently have a unit procurement cost (including canisters and other associated hardware) of about \$1.0 million, and Evolved Sea Sparrow Missiles (ESSMs), which currently have a unit procurement cost (including canisters and other associated hardware) of about \$1.4 million. The Navy's longer-range interceptor is the Standard Missile (SM). Air defense versions of the Standard Missile currently have a unit procurement cost (including containers and other associated hardware) of roughly \$4.5 million. (Source: Navy budget-justification book for Weapon Procurement, Navy [WPN] appropriation account for FY2011.) As discussed in another CRS report (CRS Report RL33745, *Navy Aegis Ballistic Missile Defense (BMD) Program: Background and Issues for Congress*, by Ronald O'Rourke), ballistic missile defense versions of the Standard Missile have unit procurement costs of \$9 million to \$15 million.

⁹ A "hard kill" involves destroying the attacking weapon in some manner. A "soft kill" involves confusing the weapon through decoys or other measures, so that it misses its intended target.

- **Deep magazine.** Navy surface ships can carry finite numbers of interceptor missiles in their missile launch tubes. Once a Navy surface ship's interceptors are fired, loading a new set of interceptors onto the ship would require the ship to temporarily withdraw from the battle. The Phalanx Close-In Weapon System (CIWS) that is installed on Navy surface ships—a radar-controlled Gatling gun that fires bursts of 20mm shells—similarly can engage a finite number of targets before it needs to be reloaded, which takes a certain amount of time. In contrast, an electrically powered laser can be fired again and again, as long as the ship has fuel to generate electricity (and sufficient cooling capacity to remove waste heat from the laser). A laser would give a ship a weapon with a deep (some observers say virtually unlimited) magazine capacity. Lasers could permit Navy surface ships to more effectively defend themselves against adversaries with more weapons and decoys than can be handled by the ships' onboard supplies of interceptor missiles and CIWS ammunition. A ship equipped with a laser, for example, could use the laser to counter an initial wave of decoys while conserving the ship's finite supply of interceptor missiles and CIWS ammunition for incoming weapons that are best countered by those systems. Future ships designed with a combination of lasers and missile-launch tubes could be smaller, and thus less expensive to procure, than future ships designed with no lasers and a larger number of missile-launch tubes.
- **Fast engagement times.** Light from a laser beam can reach a target almost instantly (eliminating the need to calculate an intercept course, as there is with interceptor missiles) and, by remaining focused on a particular spot on the target, cause disabling damage to the target within seconds. After disabling one target, a laser can be redirected in several seconds to another target. Fast engagement times can be particularly important in situations, such as near-shore operations, where missiles, rockets, artillery shells, and mortars could be fired at Navy ships from relatively close distances.
- **Ability to counter radically maneuvering air targets.** Lasers can follow and maintain their beam on radically maneuvering air targets (such as certain ASCMs) that might stress the maneuvering capabilities of Navy interceptor missiles.
- **Precision engagement and reduced risk of certain kinds of collateral damage in port areas.** Lasers are precision-engagement weapons—the light spot from a laser, which might be several inches in diameter, affects what it hits, while generally not affecting (at least not directly) separate nearby objects. Navy ships in overseas ports might be restricted in their ability to use the CIWS to defend themselves against mortars and rockets out of concern that CIWS shells that are fired upward but miss the target would eventually come back down, possibly causing collateral damage in the port area. In contrast, light from an upward-pointing laser that does not hit the target would continue flying upward in a straight line, which can reduce the chance of causing collateral damage to the port area.
- **Additional uses; graduated responses.** Lasers can perform functions other than destroying targets, including detecting and monitoring targets and producing non-

lethal effects, including reversible jamming of electro-optic (EO) sensors.¹⁰ Lasers offer the potential for graduated responses that range from warning targets to reversibly jamming their systems, to causing limited but not disabling damage (as a further warning), and then finally causing disabling damage.

Limitations

Potential limitations of shipboard lasers for countering surface, air, and ballistic missile targets include the following:

- **Line of sight.** Since laser light tends to fly through the atmosphere on an essentially straight path, shipboard lasers would be limited to line-of-sight engagements, and consequently could not counter over-the-horizon targets or targets that are obscured by intervening objects. This limits in particular potential engagement ranges against small boats, which can be obscured by higher waves, or low-flying targets. Even so, lasers can rapidly reacquire boats obscured by periodic swells, and more generally might be able to engage targets at longer ranges than certain existing shipboard gun systems. An airborne mirror, perhaps mounted on an aerostat,¹¹ could bounce light from a shipboard laser, so as to permit non-line-of-sight engagements; implementing such an arrangement would add cost and technical challenges, and the aerostat could be damaged by a misaimed shipboard laser or enemy attack.
- **Atmospheric absorption, scattering, and turbulence; not an all-weather solution.** Substances in the atmosphere—particularly water vapor, but also things such as sand, dust, salt particles, smoke, and other air pollution—absorb and scatter light from a shipboard laser, and atmospheric turbulence can defocus a laser beam. These effects can reduce the effective range of a laser. Absorption by water vapor is a particular consideration for shipboard lasers because marine environments feature substantial amounts of water vapor in the air.¹² There are certain wavelengths of light (i.e., “sweet spots” in the electromagnetic spectrum) where atmospheric absorption by water vapor is markedly reduced.¹³ Lasers can be designed to emit light at or near those sweet spots, so as to maximize their potential effectiveness. Absorption generally grows with distance to target, making it in general less of a potential problem for short-range operations than for longer-range operations. Adaptive optics, which make rapid, fine adjustments to a laser beam on a continuous basis in response to observed turbulence, can

¹⁰ Reversible jamming means that the jamming does not damage the sensor, and that the sensor can resume normal operations once the jamming ends.

¹¹ An aerostat is a lighter-than-air object, such as a dirigible or balloon, that can stay stationary in the air.

¹² For further discussion, see P. Sprangle, J.R. Peñano, A. Ting, and B. Hafizi, “Propagation of High-Energy Lasers in a Maritime Atmosphere,” *NRL Review 2004*. (Accessed online at <http://www.nrl.navy.mil/research/nrl-review/2004/featured-research/sprangle/>.)

¹³ Lasers being developed for potential shipboard use produce light with wavelengths in the near-infrared portion of the spectrum. Sweet spots in this part of the spectrum include wavelengths of 0.87 microns, 1.045 microns, 1.24 microns, 1.62 microns, 2.13 microns, and 2.2 microns. (Other sources, such as the research paper cited in footnote 12, cite somewhat different figures for sweet spot wavelengths, depending in part on whether sweet spot is for water vapor alone, or for multiple sources of atmospheric absorption and scattering.)

counteract the effects of atmospheric turbulence. Even so, lasers might not work well, or at all, in rain or fog, preventing lasers from being an all-weather solution.

- **Thermal blooming.** A laser that continues firing in the same exact direction for a certain amount of time can heat up the air it is passing through, which in turn can defocus the laser beam, reducing its ability to disable the intended target. This effect, called thermal blooming, can make lasers less effective for countering targets that are coming straight at the ship, on a constant bearing (i.e., “down-the-throat” shots). Other ship self-defense systems, such as interceptor missiles or a CIWS, might be more suitable for countering such targets. Most tests of laser systems have been against crossing targets rather than “down-the-throat” shots. In general, thermal blooming becomes more of a concern as the power of the laser beam increases.
- **Saturation attacks.** Since a laser can attack only one target at a time, requires several seconds to disable it, and several more seconds to be redirected to the next target, a laser can disable only so many targets within a given period of time. This places an upper limit on the ability of an individual laser to deal with saturation attacks—attacks by multiple weapons that approach the ship simultaneously or within a few seconds of one another. This limitation can be mitigated by installing more than one laser on the ship, similar to how the Navy installs multiple CIWS systems on certain ships.¹⁴
- **Hardened targets and countermeasures.** Less-powerful lasers—that is, lasers with beam powers measured in kilowatts (kW) rather than megawatts (MW)¹⁵—can have less effectiveness against targets that incorporate shielding, ablative material, or highly reflective surfaces, or that rotate rapidly (so that the laser spot does not remain continuously on a single location on the target’s surface) or tumble. Small boats could employ smoke or other obscurants to reduce their susceptibility to laser attack. Measures such as these, however, can increase the cost and/or weight of a weapon, and obscurants could make it more difficult for small boat operators to see what is around them, reducing their ability to use their boats effectively.
- **Risk of collateral damage to aircraft and satellites.** Since light from an upward-pointing laser that does not hit the target would continue flying upward in a straight line, it could pose a risk of causing unwanted collateral damage to aircraft and satellites.¹⁶

In addition to the above points, a shipboard laser, like other shipboard systems, would take up space on a ship, use up some of the ship’s weight-carrying capacity, create a load on the ship’s electrical power and cooling systems, and possibly alter the ship’s radar cross section. These considerations—referred to collectively as ship impact—can become significant when

¹⁴ The Navy installs multiple CIWS systems on certain ships not only to improve their ability to handle a saturation attack, but also to ensure that each ship has full (i.e., 360-degree CIWS) coverage around the ship. A desire for 360-degree laser coverage could be another reason for installing multiple lasers on a ship.

¹⁵ For a discussion of laser power levels, see “Required Laser Power Levels for Countering Targets.”

¹⁶ For more on the issue of collateral damage to satellites, see **Appendix J**.

considering whether to backfit lasers onto existing ships, or whether to incorporate lasers into new ship designs.¹⁷

Potential Targets for Shipboard Lasers

Potential targets for shipboard lasers include the following:

- electro-optical (EO) sensors, including those on anti-ship missiles;
- small boats (including so-called “swarm boats”)¹⁸ and other watercraft (such as jet skis);
- rockets, artillery shells, mortars (sometimes collectively referred to as RAM);
- UAVs;
- manned aircraft;
- ASCMs; and
- ballistic missiles, including ASBMs.

Small boats, rockets, artillery shells, and mortars can be a particular concern for Navy surface ships during operations close to shore. Iran has acquired large numbers of swarm boats for potential use during a crisis or conflict against U.S. Navy ships seeking to enter or operate in the Persian Gulf. RAM weapons are widely proliferated to both state and non-state organizations. UAVs, including relatively simple and inexpensive models, can be used to collect and transmit targeting data on Navy ships, attack Navy ships directly by diving into them, and be armed to attack Navy ships at a distance. ASCMs are widely proliferated to state actors, and were also reportedly used by the non-state Hezbollah organization in 2006 to attack an Israeli warship. China has developed an ASBM. Lasers that are not capable of disabling ballistic missiles could nevertheless augment ballistic missile defense operations by being used for precision tracking and imaging.

Required Laser Power Levels for Countering Targets

A laser’s ability to disable a target depends in large part on the power and beam quality of its light beam. The power of the light beam is measured in kilowatts (kW) or megawatts (MW). Beam quality (BQ) is a measure of how well focused the beam is.¹⁹ Additional factors affecting a laser’s ability to disable a target include:

¹⁷ For an additional (and somewhat similar) discussion of the potential advantages and limitations of lasers, see Richard J. Dunn, III, *Operational Implications of Laser Weapons*, Northrop Grumman Analysis Center Papers, September 2005, pp. 10-12.

¹⁸ Swarm boats are small, fast boats that attack a larger ship by operating in packs, or swarms, so as to present the larger ship with a complex situation of many hostile platforms that are moving rapidly around the ship in different directions.

¹⁹ A laser with perfect BQ – meaning that the laser’s light spot is focused to the physical diffraction limit – is said to have a BQ of 1.0. A beam that is focused to the physical diffraction limit is focused as well as the laws of nature allow. Lasers with the wavelengths considered in this report that are focused to the physical diffraction limit would, if fired in a vacuum, experience very little spreading out of the laser spot as the beam travels further and further from the source. A BQ of 2.0 means that the laser’s light spot at a given range is twice as large in diameter as an otherwise-same laser (continued...)

- atmospheric absorption, scattering, and turbulence,²⁰
- jitter—the degree to which the spot of laser light jumps around on the surface of the target due to vibration or other movement of the laser system,²¹ and
- target design features, which can affect a target’s susceptibility to laser damage.

Table A-1 in **Appendix A** summarizes some government and industry perspectives regarding power levels needed to counter certain targets. Although these perspectives differ somewhat, the following conclusions might be drawn from the table regarding approximate laser power levels needed to affect certain targets:

- **Lasers with a power level of about 10 kW** might be able to counter some UAVs at short range, particularly “soft” UAVs (i.e., those with design features that make them particularly susceptible to laser damage).
- **Lasers with power levels in the tens of kilowatts** could have more capability for countering UAVs, and could counter at least some small boats as well.
- **Lasers with a power level of about 100 kW** would have a greater ability for countering UAVs and small boats, as well as some capability for countering rockets, artillery, and mortars.
- **Lasers with power levels in the hundreds of kilowatts** could have greater ability for countering targets mentioned above, and could also counter manned aircraft and some missiles.
- **Lasers with power levels in the megawatts** could have greater ability for countering targets mentioned above—including supersonic ASCMs and ballistic missiles—at ranges of up to about 10 nautical miles.

In addition to the points above, one Navy briefing stated that lasers with power levels above 300 kW could permit a ship to defend not only itself, but other ships in the area as well (a capability referred to as area defense or escort operations or battle group operations).

Types of Lasers Being Developed for Potential Shipboard Use

The Navy and DOD are developing three principal types of lasers for potential use on Navy surface ships:

- fiber solid state lasers (SSLs),
- slab SSLs, and
- free electron lasers (FELs).

(...continued)

with a BQ of 1. The Navy considers a BQ of 1.1 to 5 to be high, and a BQ of 5.1 to 20 to be moderate. Achieving a BQ of 1 to 5 generally adds complexity and cost to the system. In general, the longer the range to the target, the more important BQ becomes.

²⁰ As discussed earlier, atmospheric absorption, scattering, and turbulence are affected by the laser’s light wavelength and the use of adaptive optics.

²¹ Jitter becomes more important as BQ improves and range increases.

All three types are electrically powered.²² Each type is discussed briefly below. Additional information on each type is presented in **Appendix C** through **Appendix F**.

Fiber Solid State Lasers (Fiber SSLs)

Fiber solid state lasers (SSLs) are widely used in industry—tens of thousands are used by auto and truck manufacturing firms for cutting and welding metal. Consequently, they are considered to be a very robust technology.

Laser Weapon System (LaWS)

One fiber SSL prototype demonstrator developed by the Navy, called the **Laser Weapon System (LaWS)**, had a beam power of 33 kW. The Navy at one point envisioned LaWS being used for operations such as disabling or reversibly jamming EO sensors, countering UAVs and EO guided missiles, and augmenting radar tracking. The Navy envisioned installing LaWS on a ship either on its own mount or (more likely) as an add-on to an existing Phalanx Close-In Weapon System (CIWS) mount.²³ The Navy funded work to integrate LaWS with CIWS, to support the latter option.

The Navy has stated the following regarding tests of LaWS:

- In June 2009, LaWS successfully engaged five threat-representative UAVs²⁴ in five attempts in tests in combat-representative scenarios in a desert setting at the Naval Air Weapons Station at China Lake, in southern California.
- In May 2010, LaWS successfully engaged four threat-representative UAVs in four attempts in combat-representative scenarios at a range of about one nautical mile in an over-the-water setting conducted from San Nicholas Island, off the coast of southern California. LaWS during these tests also demonstrated an ability to destroy materials used in rigid-hull inflatable boats (RHIBs—a type of small boat) at a range of about half a nautical mile, and to reversibly jam and disrupt electro-optical/infrared sensors.²⁵

²² Some military lasers, such as the Air Force's Airborne laser (ABL), are chemically powered. Development work on potential shipboard lasers focuses on electrically powered lasers because such lasers can be powered by a ship's existing electrical power system, whereas a chemically powered laser would require the ship to be periodically resupplied with the chemicals used by the laser. Resupplying the ship with the chemicals could require the ship to temporarily remove itself from the battle. In addition, the Navy would need to establish a new logistics train to provide the chemicals to Navy surface ships, and loading and storing the chemicals on ships would create a handling risk for crew members, since the chemicals in question are toxic.

²³ As mentioned earlier the Phalanx CIWS is a radar-controlled Gatling gun that fires bursts of 20mm shells.

²⁴ Threat-representative means that the UAV is generally similar in design and capabilities to UAVs operated by potential adversaries.

²⁵ For a Navy press release about this test, see NAVSEA (Naval Sea Systems Command) press release dated May 28, 2010, and entitled "Navy Laser Destroys Unmanned Aerial Vehicle in a Maritime Environment," accessed online at http://www.navsea.navy.mil/PR2010/PressRelease_20100528_Laser%20Destroys%20UAV.pdf. The UAVs engaged in these tests were BQM-147s, which various sources describe as low-cost, propeller-driven UAVs with a length of about 5 feet, a wingspan of about 8 feet, and a maximum speed of 100 knots or less.

- Between July and September 2012, LaWS successfully engaged three UAVs in three attempts in tests during which the system was aboard the Arleigh Burke (DDG-51) class destroyer *Dewey* (DDG-105) in waters off San Diego.²⁶

The Navy at one point envisioned scaling up the power of the LaWS beam to about 100 kW by FY2014. How much beyond 100 kW the system could eventually be scaled up to was not clear, but the system was not generally viewed as having the potential for being scaled up to megawatt power levels.

The Navy stated that as of June 2010, the Technology Readiness Level (TRL) of the LaWS prototype “is approaching 6, based on a system prototype demonstration in a relevant (maritime) environment.”²⁷ The Navy estimated that it might cost roughly \$150 million to develop LaWS to TRL 7, meaning the demonstration of a system prototype in an operational environment. The Navy considered the LaWS effort to be ready for conversion into a program of record, should policymakers decide that this would be desirable. If the LaWS effort were converted soon into a POR, the Navy believed a production version of LaWS might achieve Initial Operational Capability (or IOC—a type of official in-service date) on Navy surface ships around FY2017. The Navy estimated that production copies of the LaWS system could be installed and procured as additions to ship CIWS mounts for a total cost of roughly \$17 million per CIWS mount.²⁸

On April 8, 2013, the Navy announced that it would install LaWS on the USS Ponce, a converted amphibious ship that is stationed in the Persian Gulf as an Afloat Forward Staging Base (AFSB). LaWS will be installed on the Ponce (pronounced pon-SAY) in early 2014 to conduct evaluation of shipboard lasers in an operational setting.²⁹ Whether the operating characteristics of LaWS as installed on the Ponce will be unchanged from those mentioned above is not clear.

For additional information on fiber SSLs and LaWS, see **Appendix C**.

²⁶ Mike McCarthy, “Navy Deploying Laser For Taking Out Drones,” *Defense Daily*, April 9, 2013; Graham Warwick, “U.S. Navy Planning Gulf Deployment For Laser Weapon,” *Aerospace Daily & Defense Report*, April 9, 2013: 6.

²⁷ Source: Navy information paper dated June 6, 2011, provided by the Navy to CRS and CBO on June 14, 2011. DOD uses TRL ratings to characterize the developmental status of many weapon technologies. DOD TRL ratings range from 1 (basic principles observed and reported) to 9 (actual system proven through successful mission operations). For the definitions of all 9 DOD TRL ratings, see **Appendix H**.

²⁸ The \$17 million figure was provided in a Navy briefing to CRS. A May 11, 2010, press report quoted a Navy official as estimating the cost at \$15 million:

“I think the total system, when we finally get it out there, will be on the order of \$15 million per system and then there will be no ordnance costs, no logistics tail for maintaining the ordnance, no depots to overhaul ordnance, and no fire suppression as you move this ordnance around,” [Capt. Dave Kiel, Naval Sea Systems Command (NAVSEA) directed energy and electric weapons program manager] said.

(Geoff Fein, “Navy Leveraging Commercial Lasers To Shoot Down UAVs,” *Defense Daily*, May 11, 2010: 3-4.)

²⁹ “Navy Leaders Announce Plans for Deploying Cost-Saving Laser Technology,” *Navy News Service*, April 8, 2013; Thom Shanker, “Navy Deploying Laser Weapon Prototype Near Iran,” *New York Times*, April 9, 2013: 4; Mike McCarthy, “Navy Deploying Laser For Taking Out Drones,” *Defense Daily*, April 9, 2013; Graham Warwick, “U.S. Navy Planning Gulf Deployment For Laser Weapon,” *Aerospace Daily & Defense Report*, April 9, 2013: 6; Megan Eckstein, “Navy-Built Laser Weapon System Will Begin Demo On Ponce In Early 2014,” *Inside the Navy*, April 15, 2013;

Tactical Laser System

Another Navy fiber SSL effort is the **Tactical Laser System (TLS)**—a laser with a beam power of 10 kW that is designed to be added to the Mk 38 25 mm machine guns installed on the decks of many Navy surface ships.³⁰ TLS would augment the Mk 38 machine gun in countering targets such as small boats; it could also assist in providing precise tracking of targets. The Navy in March 2011 awarded a \$2.8 million contract to BAE to develop a prototype of the TLS over a 15-month period.³¹ Boeing is collaborating with BAE on the project. The TLS effort was initiated following a January 2008 incident involving Iranian small boats. The effort is financed in part by \$2.991 million in FY2010 funding that Congress added to the Navy’s research and development account in PE 0603795N, Land Attack Technology, for the purpose of improving the capability of the Mk 38 system.

A March 26, 2012, press report states that “[Michael] Rinn, [Boeing’s vice president for directed energy systems], said the project, which gets a small amount of Navy funding and is supplemented by internal investments from both companies, has had several successes over the past few years. Field testing of the major components last summer at Eglin Air Force Base in Florida showed the system could distinguish between friendly and enemy activities in both daytime and nighttime, for example.” The report states that full system testing of the laser was scheduled for the summer of 2012.³²

A January 28, 2013, press report states that “BAE Systems and Boeing are pushing their Mark 38 Tactical Laser System through intense internally-funded testing, hoping to get onto a ship for at-sea testing as soon as one is available, company officials said earlier this month.” The article stated that Mark Rinn, a Boeing official, “said testing in December [2012] went well and showed successful engagements at ‘several thousands of meters.’ He had hoped to include unmanned aerial vehicles in the set of targets for the Mark 38 Tactical Laser System—the weapon system has already shot at targets on land and on water—but the companies could not get permission in time. He said that they would have permission for counter-UAV testing before the next round of tests this spring.”³³

For additional information on TLS, see **Appendix D**.

Slab Solid State Lasers (Slab SSLs)

DOD has pursued multiple efforts to develop slab SSLs for military use. Among these was the **Maritime Laser Demonstration (MLD)**, a prototype laser weapon developed as a rapid demonstration project under DOD’s Joint High Power SSL (JHPSSL) program. MLD leveraged

³⁰ Carlo Munoz, “New Laser-Based Weapon For Navy Fleet Protection Operations In The Works,” *Defense Daily*, April 11, 2011. See also Marc Selinger, “Lasers on the High Seas,” <http://www.boeing.com>, November 28, 2011, accessed November 28, 2011, at http://www.boeing.com/Features/2011/11/bds_tls_11_28_11.html.

³¹ BAE Systems press release dated April 7, 2011, entitled “BAE Systems Selected to Demonstrate Tactical Laser System for the U.S. Navy;” Carlo Munoz, “New Laser-Based Weapon For Navy Fleet Protection Operations In The Works,” *Defense Daily*, April 11, 2011.

³² Megan Eckstein, “FEL Looks Good At CDR, But Project Halted In Favor of SSL Development,” *Inside the Navy*, March 26, 2012.

³³ Megan Eckstein, “BAE, Boeing Pushing To Get Tactical Laser System To At-Sea Testing,” *Inside the Navy*, January 28, 2013.

development work on slab SSLs done elsewhere in DOD under the JHPSSL program. In March 2009, Northrop demonstrated a version of MLD that coherently combined seven slab SSLs, each with a power of about 15 kW, to create a beam with a power of about 105 kW.

In July 2010, the ability of MLD to track small boats in a marine environment was tested at NSWC Port Hueneme, CA.³⁴ In late August and early September 2010, MLD was tested in an over-the-water setting at the Navy's Potomac River Test Range against stationary targets, including representative small boat sections.³⁵ In November 2010, an at-sea test of the system against small boat targets reportedly was stopped midway because one of the system's components needed to be replaced.³⁶ The test was resumed in April 2011, and on April 6, 2011, the system successfully engaged a small target vessel. According to the Navy, this was the first time that a laser of that energy level had been put on a Navy ship, powered from that ship, and used to counter a target at range in a maritime environment.³⁷ In May 2011, Northrop stated that it could build the first unit of a full-power engineering and manufacturing development (EMD) version of the weapon within four years, if the Navy could find the resources to fund the effort.³⁸

Scaling up a slab laser to a total power of 300 kW is not considered to require any technological breakthroughs. Supporters of slab SSLs such as MLD believe they could eventually be scaled up further, to perhaps 600 kW. Slab SSLs are not generally viewed as easily scalable to megawatt power levels.

The Navy stated that as of December 2010, MLD was at a Technology Readiness Level (TRL) of 5, meaning component and/or breadboard validation in a relevant environment.³⁹

For additional information on slab SSLs and MLD, see **Appendix E**.

Free Electron Lasers (FELs)

Unlike slab SSLs, which are being developed by multiple U.S. military services, FELs are being developed within DOD solely by the Navy, in part because they would be too large to be installed on Army or Marine Corps ground vehicles or Air Force tactical aircraft, and in part because an FEL's ability to change its wavelength so as to match atmospheric transmission sweet spots

³⁴ See Northrop Grumman press release dated July 26, 2010, and entitled "Northrop Grumman-Built Maritime Laser Demonstration System Proves Key Capabilities for Shipboard Operations, Weaponization," accessed online at http://www.irconnect.com/noc/press/pages/news_releases.html?d=197321.

³⁵ See Northrop Grumman press release dated September 30, 2010, and entitled "Northrop Grumman-Built Maritime Laser Demonstration System Shows Higher Lethality, Longer Ranges at Potomac River Test Range; U.S. Navy Solid-State Laser's Mature Technology is Ready for Marine Environment;" accessed online at http://www.irconnect.com/noc/press/pages/news_releases.html?d=202703.

³⁶ Andrew Burt, "Navy's First At-Sea Maritime laser Weapon Test Encounters Delays," *Inside the Navy*, November 15, 2010.

³⁷ Geoff S. Fein, "MLD Test Moves Navy a Step Closer to Lasers for Ship Self-Defense," April 8, 2011 (Office of Naval Research news release, accessed online at <http://www.onr.navy.mil/en/Media-Center/Press-Releases/2011/Maritime-Laser-MLD-Test.aspx>.)

³⁸ Graham Warwick, "Northrop To Offer High-Power Ship Laser Within Four Years," *Aerospace Daily & Defense Report*, May 16, 2011: 4.

³⁹ Source: Navy information paper dated December 3, 2010, provided by the Navy to CRS on December 3, 2010. As mentioned in footnote 27, DOD uses TRL ratings to characterize the developmental status of many weapon technologies. DOD TRL ratings range from 1 (basic principles observed and reported) to 9 (actual system proven through successful mission operations). For the definitions of all 9 DOD TRL ratings, see **Appendix H**.

makes it particularly suited for operations in a marine environment. The basic architecture of an FEL offers a clear potential for scaling up to power levels of one or more megawatts.

A 14.7 kW FEL has been developed; it has not been moved out of a laboratory setting or fired at an operational moving target. The Office of Naval Research (ONR) had planned to follow this with the development, as an Innovative Naval Prototype (INP),⁴⁰ of a 100 kW FEL; the work was scheduled to be performed during FY2010-FY2015.⁴¹ Developing a 100 kW FEL would reduce the risks associated with developing a megawatt-class FEL. A March 26, 2011, press report, however, states that “the Navy is putting the project on the back burner as it focuses on a solid-state laser as the quickest way to get a directed-energy weapon to the fleet.” The report states that “[Roger] McGinnis, [program executive for INPs at ONR’s Naval Air Warfare and Weapons Department], said the Navy had previously wanted to pursue a 100 kilowatt FEL gun as an intermediate step toward the megawatt gun but decided to instead focus on maturing the critical technology components with an Energy department lab or small industry partners....”⁴²

The Navy states that as of December 2010, FEL was at a Technology Readiness Level (TRL) of 4 (meaning component and/or breadboard validation in a laboratory environment).⁴³

For additional information on FEL, see **Appendix F**.

Navy Surface Fleet’s Generalized Vision for Shipboard Lasers

The Navy’s surface fleet has a three-phase generalized vision for shipboard high-energy lasers that is summarized in **Table 1**. Although this generalized vision refers to lasers of certain power levels and potential time frames for installing lasers on Navy ships, it is not a program of record for procuring a production version of a shipboard laser, or a roadmap for shipboard lasers (which would be more specific than a generalized vision). The Navy currently does not have such a program of record or roadmap.

⁴⁰ For a description of INPs, see **Appendix G**.

⁴¹ A low power Terahertz Sensor FEL is also being developed under the INP, with a prototype scheduled to be available in FY2015. ONR states that “Possible uses of this system include [target] interrogation, sensing and discrimination of high value targets, and weapons of mass destruction detection.”

⁴² Megan Eckstein, “FEL Looks Good At CDR, But Project Halted In Favor of SSL Development,” *Inside the Navy*, March 26, 2012.

⁴³ Source: Navy information paper dated December 3, 2010, provided by the Navy to CRS on December 3, 2010. As mentioned in footnote 27, DOD uses TRL ratings to characterize the developmental status of many weapon technologies. DOD TRL ratings range from 1 (basic principles observed and reported) to 9 (actual system proven through successful mission operations). For the definitions of all 9 DOD TRL ratings, see **Appendix H**.

Table I. Surface Navy’s Generalized Vision for Shipboard High-Energy Lasers
(Draft version as of May 2011)

	Initial capability	Added capability	Added capability
Laser’s beam power	60 kW to 100 kW	300 kW to 500 kW	> 1 MW
Missions	Countering UAVs, EO-guided ASCMs, enemy ISR systems, and swarm boats, and used for precise tracking to support air defense missions conducted by electromagnetic rail gun (EMRG), ballistic missile defense (BMD) missions, augmenting the ship’s radar, and enhancing general situational awareness	Capabilities in previous column, but with added range and a capability to counter ASCMs flying a crossing path toward another ship.	Capabilities in previous column, but a capability for full-self defense operations against ASCMs and maneuvering reentry vehicles (MaRVs), and full BMD missions
Required ship power (in kW or MW) and cooling capacity (in tons) ^a	<400 kW and 68 tons	<2.5MW and 560 tons	~10-20 MW and ~1,400 tons
Current weapon system TRL	5	4	2-3
Earliest potential IOC	2017	~2022	after 2025
Applicable ships	Could be backfit onto existing ships, as well as installed on new ships	Could be installed on future surface combatants, including potentially the Flight III DDG-51	Could be installed on future surface combatants, ships with integrated propulsion systems, and aircraft carriers

Source: U.S. Navy briefing slide dated May 20, 2011, and provided to CRS and CBO at a briefing on that date.

a. Power and cooling requirements assume continuous firing of the laser with a 67% duty cycle (i.e., the laser is firing 67% of the time).

Remaining Technical Challenges

Navy and DOD research on military lasers has overcome many of the technical challenges associated with developing shipboard lasers, but a number of challenges remain. Remaining technical challenges for potential shipboard lasers can be grouped into four broad categories:

- scaling up beam power to higher levels while maintaining or improving beam quality and addressing thermal management (the removal of waste heat from the gain medium);
- turning prototype and demonstration versions of lasers into versions that are suitable for series production, shipboard installation, and shipboard operation and maintenance over many years of use;
- engineering other parts of a complete laser weapon system, including target detection and tracking, and beam pointing; and

- integrating lasers with ship power and cooling systems, and with ship combat systems (i.e., a ship's integrated collection of sensors, computers, displays, and weapons).

Although these challenges are stated briefly here, they are not trivial. Skeptics might argue that certain past DOD laser development efforts proved over-optimistic in terms of projections for overcoming technical challenges and producing operational weapons. In spite of decades of development work, these skeptics might note, DOD has not deployed an operational high-energy laser weapon system.

Scaling up beam power to megawatt levels is a principal challenge at this point for the FEL. ONR believes that scaling up FEL from 14 kW to 100 kW will make it substantially easier to then scale up FEL to megawatt power levels. Thermal management is a particular challenge for SSLs. (Supporters of fiber SSLs say it is less of a challenge for fiber SSLs than for slab SSLs.) Supporters of LaWS argue that many of the challenges associated with fielding the system have been overcome; a May 11, 2010, press report states:

Taking a laser weapon from land to sea presents a few challenges, [Capt. Dave Kiel, Naval Sea Systems Command directed energy and electric weapons program manager] said. "To me, all the technical challenges that exist to moving to a maritime environment are really just engineering issues. I don't think there will be any significant S&T [science and technology] issues."

The issues range from stabilizing the system to the effect that higher humidity has on absorbing some of a lasers power as it passes through the atmosphere, he said.

"The biggest issues though aren't purely technical they are related to just the whole socialization issue—no one has ever had a laser weapon on a ship before and it is going to take people time to get used to them," Kiel added.⁴⁴

That means making sure the laser does what it is advertised to do and that every time the system is turned on, no one is going to be blinded from the laser, he said.⁴⁵

ONR Solid-State Laser Technology Maturation Effort

A May 8, 2012, press report from the Navy's own news service states:

To help Sailors defeat small boat threats and aerial targets without using bullets, the Office of Naval Research (ONR) wants to develop a solid-state laser weapon prototype that will demonstrate multi-mission capabilities aboard a Navy ship, officials announced May 8.

"We believe it's time to move forward with solid-state lasers and shift the focus from limited demonstrations to weapon prototype development and related technology advancement," said Peter Morrison, program officer of the Solid-State Laser Technology Maturation (SSL-TM) program.

⁴⁴ The term socialization as used by DOD personnel generally refers to the process in which people learn about and become comfortable with a new idea or technology.

⁴⁵ Geoff Fein, "Navy Leveraging Commercial Lasers To Shoot Down UAVs," *Defense Daily*, May 11, 2010: 3-4.

ONR will host an industry day, May 16, to provide the research and development community with information about the program. A Broad Agency Announcement is expected to be released thereafter to solicit proposals and bids.

The Navy's long history of advancing directed-energy technology has yielded kilowatt-scale lasers capable of being employed as weapons. Among the programs, the Maritime Laser Demonstration developed a proof-of-concept technology that was tested at sea aboard a decommissioned Navy ship. The demonstrator was able to disable a small boat target. Another program, the Laser Weapon System, demonstrated a similar ability to shoot down four small unmanned test aircraft.

The SSL-TM program builds upon ONR's directed-energy developments and knowledge gained from other laser research initiatives, including the MK 38 Tactical Laser Demonstration tested at Eglin Air Force Base, Fla. All of these efforts could help the Department of the Navy become the first of the armed forces to deploy high-energy laser weapons.⁴⁶

On August 14, 2012, ONR released a broad agency announcement (BAA) for the above-described SSL technology maturation effort. ONR will select up to four proposals; winning bidders will receive six-month Phase I contracts worth up to \$1.5 million each. Up to two of the bidders will then be selected to continue work under Phases II through IV, taking the effort through prototype development and demonstration.⁴⁷

Naval Directed Energy Steering Group

In June 2012, it was reported that the Navy in December 2011 formed a Naval Directed Energy Steering Group (NDESG) to develop a naval directed energy vision, strategy, and roadmap. The December 12, 2011, Navy memorandum establishing the steering group states in part:

A key to future Navy and Marine Corps war fighting capabilities is the efficient, effective and rapid development, acquisition, and fielding of advanced technologies having game-changing capabilities across a range of mission areas. Directed Energy Weapon (DEW) technologies, including lasers and high power microwave (HPM) weapons, may offer our naval forces such game-changing potential....

The Naval DE Steering Group (NDESG) is formed as a Secretary of the Navy (SECNAV) initiative to deliver a synchronized, fiscally-informed strategy that aligns DE investments with roadmaps across the Doctrine, Organization, Training, Material, Leadership and Education, Personnel and Facilities (DOTMLPF) spectrum [of naval activities] to address near-term fleet capability gaps and the long-range vision for the implementation of DE in the fleet. The NDESG will be the formal engine to drive this effort....

The NDESG will have the following objectives:

⁴⁶ Grace Jean, Office of Naval Research Public Affairs, "New ONR Program Aims to Develop Solid-State Laser Weapons for Ships," *Navy News Service*, May 8, 2012, accessed June 27, 2012 at http://www.navy.mil/submit/display.asp?story_id=67041. See also Graham Warwick, Navy Plans Solid-State Laser Weapon Prototype," *Aerospace Daily & Defense Report*, May 10, 2012: 2-3; and Megan Eckstein, "ONR Creates Solid-State Laser Technology Maturation Program," *Inside the Navy*, May 14, 2012.

⁴⁷ Megan Eckstein, "ONR Planning First Solid-State Laser Weapon Prototypes On DDG, LCS," *Inside the Navy*, August 20, 2012.

a. Develop a DON Naval DE Vision and Strategy.... A Directed Energy vision is necessary to provide DON leadership's depiction of desired DEW capabilities and DE countermeasures as deployed and employed across U.S. naval forces. A supporting DE strategy would be used to establish strategic goals, guiding principles, mission area priorities, roles and responsibilities and overarching objectives regarding the acquisition and fielding of DEW across the Navy and Marine Corps.

b. Develop a comprehensive DE roadmap... based on the overarching vision and strategy. The proposed roadmap would address the prioritized mission needs across all naval forces and the associated DE technologies that can be fielded to satisfy those mission needs in the near-term (2-5) years, mid-term (5-10 years) and far-term (10-20 years).

c. Provide assessments on Science & Technology (S&T)/Research & Development (R&D) and oversee the development and transition of DE systems and technologies to the Fleet, including non-material efforts⁴⁸ to integrate these new capabilities into existing operational concepts and procedures....

The NDESG will provide a draft vision and strategy with initial plan of actions and milestones to the UNDERSECNAV [Under Secretary of the Navy] within 90 days of the promulgation of this charter.⁴⁹

Regarding the steering group's objective to develop a directed energy roadmap, it can be noted that the Navy in recent years has developed or called for the development of roadmaps or master plans in a number of other technology and policy areas, including the Navy's future computing and information environment,⁵⁰ information dominance,⁵¹ UAVs,⁵² unmanned underwater vehicles (UUVs),⁵³ unmanned surface vehicles (USVs),⁵⁴ the Navy's response to changing conditions in the Arctic,⁵⁵ the Navy's response to climate change,⁵⁶ and military transformation of the Navy.⁵⁷

⁴⁸ The term non-material efforts refers to actions other than the acquisition of new or modernized equipment, such as making changes in doctrine or tactics.

⁴⁹ Memorandum dated December 12, 2011, from the Under Secretary of the Navy, to various Navy offices, on the subject: "Naval Directed Energy Steering Group Charter," posted at InsideDefense.com (subscription required) June 18, 2012. See also: Megan Eckstein, "Naval Directed-Energy Steering Group Outlining Future Of DE Weapons," *Inside the Navy*, June 15, 2012.

⁵⁰ See, for example, Andrew Burt, "Roughead Seeks 'Revolutionary' Concepts In Information and Computing," *Inside the Navy*, October 11, 2010.

⁵¹ See, for example, Andrew Burt, "Navy Approves Three of 14 Information Dominance Roadmaps," *Inside the Navy*, September 10, 2010; "Notes from the Armed Forces Communications and Electronics Association and U.S. Naval Institute's West 2010 Conference," *Inside the Navy*, February 8, 2010.

⁵² See, for example, "Navy Roadmap Calls For Spiral Development Of Fire Scout UAV," *Inside the Navy*, August 2, 2010.

⁵³ See, for example, Cid Standifer, "Navy To Work With Air Force To Analyze And Exploit Intelligence Data," *Inside the Navy*, July 30, 2010.

⁵⁴ Emelie Rutherford, "Navy To Unveil Master Plan for Unmanned Surface Vehicles This Month," *Inside the Navy*, September 10, 2007.

⁵⁵ For more on the Navy's Arctic roadmap, see CRS Report R41153, *Changes in the Arctic: Background and Issues for Congress*, coordinated by Ronald O'Rourke.

⁵⁶ See, for example, Zachary M. Peterson, "Navy Issues Climate Change Roadmap, Defers Investments Pending Study," *Inside the Navy*, May 31, 2010.

⁵⁷ See, for example, Randy Woods, "'Naval Transformation Roadmap' Fleshes Out 'Seapower 21' Vision," *Inside the Navy*, July 8, 2002.

Directed Energy Vision for U.S. Naval Forces

The directed energy vision and the directed energy strategy called for in paragraph (a) of the memorandum quoted in the previous section have been developed. The text of the vision statement is as follows:

A Directed Energy Vision for U.S. Naval Forces

Guidance from the Secretary of Defense promulgated in Priorities for 21st Century Defense in January 2012 directs the Department to “sustain key streams of innovation that may provide significant long-term payoffs.” Directed-energy (DE) technology not only offers the prospect for a major return on investment over the long term, it could begin paying significant dividends within the current future years defense plan (FYDP) by addressing immediate combatant commander requirements and enabling fleet experimentation focused on emerging threats, including anti-access and area-denial challenges.

Military applications of DE technology hold growing promise for gaining and sustaining tactical, operational, and strategic advantage for U.S. forces across the full range of military operations. They could have significant effects across multiple dimensions of the battlespace: maritime, air, land, space, and cyberspace. Directed energy weapons (DEWs) offer several potentially “game changing” advantages: very rapid engagement, low cost per engagement, essentially infinite magazines, and low total ownership costs. DEWs and their associated platform integration technologies must be properly resourced across the FYDP to ensure that our Navy and Marine Corps Team maintains its warfighting edge over prospective adversaries, including those aggressively pursuing DEWs.

DEWs affect a target by imparting non-kinetic, or electromagnetic, energy. DEW technologies can operate in any part of the electromagnetic spectrum and typically fall into the categories of either lasers (i.e., low, medium, or high power) or high-power radio frequency (i.e., high-power microwave, radio frequency (RF), microwave, and millimeter wave (MMW)). DEW technologies and systems use electromagnetic energy to cause persistent disruption, reversible effects or permanent damage by attacking target materials, electronics, optics, antennas, and sensors, including non-lethal counter-personnel and counter-materiel applications. The ability of these weapons to incapacitate, disrupt, damage, disable, or destroy targets has been proven with numerous demonstrations of lethal and non-lethal effects carried out in laboratory, field testing and evaluation, and successful employment on the battlefield.

The DoN [Department of the Navy] will focus its DE investments on those technologies that address critical Navy and Marine Corps capability gaps. Given the surface fleet’s ability to overcome the technical challenges associated with the military exploitation of high power, long range DEW—including power, cooling, weight, and volume requirements—it is the logical vanguard for demonstrating the potential of first-generation weapons. Across the spectrum of DEWs, early applications will focus on supporting forward deployed forces to defeat Improvised Explosive Devices (IEDs); artillery, mortars, and rockets; intelligence, surveillance and reconnaissance systems; fast-attack craft; fixed and rotary-wing aviation; and subsonic anti-ship cruise missiles. The longer term objective is to field higher power systems capable of defeating supersonic cruise missiles and selected ballistic missiles.

As the technology matures to increase energy efficiency and reduce form factors, DEWs will be integrated into ground vehicles to support fire and maneuver in contested environments, to include conducting low-collateral damage strikes in built-up terrain, employing non-lethal DEW to segregate and isolate enemy from civilians, and defending against increasingly ubiquitous guided rockets, artillery, mortars, and missiles. DE applications for fixed- and

rotary-wing aircraft will focus both on offensive and defensive air-to-air, air-to-surface, and air-to-ground missions. Early applications will focus on countering surface-to-air and small boat threats, as well as conducting precision strikes with mission-tailored lethality.

The DoN will field initial DEW capabilities in the near-term to provide our fleet and operating forces with the ability to address identified critical mission capability gaps while learning invaluable fielding and employment lessons that will inform our way ahead. Innovation has been the hallmark of U.S. Naval Forces. DEWs represent another naval innovation that when transitioned from the laboratory to battlefield will help our Navy and Marine Corps Team to sustain its technological advantage and win our nation's battles. Towards this end, the DoN will take a measured approach toward DEW S&T and R&D activities and their transition to acquisition programs based on operational requirements, technological maturity or readiness, demonstrated performance, ease of systems integration and affordability.

The DoN will address the defensive challenges posed by diffusion and maturation of DEWs available to prospective adversaries. These efforts will guide the development and fielding of countermeasures, DEW-resistant systems, and effective non-material solutions across the maritime battlespace domain. While high-power DEWs will be limited to nation states that choose to pursue them, lower power weapons will become increasingly available at a relatively low cost to non-state actors.

Finally, the DoN will coordinate with other Services and agencies to ensure policies and rules of engagement are in place to enable our Sailors and Marines to operationally employ DEWs effectively. In addition, we will develop not only the DEWs themselves but the sensors, communications, and control technologies that will enable DEWs to operate, in combination with other military capabilities, at their full potential.⁵⁸

Destroyers and LCSs Reportedly Leading Candidate Platforms

An August 20, 2012, press report stated that following the MLD effort, the Navy conducted studies to examine the ability of various Navy ship classes to accept SSLs. The report quoted Peter Morrison, ONR's SSL program manager, as saying that based on these studies, "the DDG [destroyer] and LCS [Littoral Combat Ship] classes ... provided the best opportunity to match new capabilities with emerging needs with higher-energy laser weapons capabilities, and the class' forecasts for power, cooling, space and weight." The report stated that the Navy continues to review the potential for installing SSLs on other types of ships as well.⁵⁹

FY2014 Funding Request

The Navy's proposed FY2014 budget requests \$40.4 million for research and development work on directed energy technologies, including the FEL program and SSL technologies. The work forms part of Program Element (PE) 0602114N, Power Projection Applied Research, in the Navy's research and development account. The Navy requested \$31.7 million for FY2013 for

⁵⁸ Department of the Navy, *A Directed Energy Vision for U.S. Naval Forces*, 2 pp., provided to CRS by Navy Office of Legislative Affairs, August 20, 2012. Emphasis as in original.

⁵⁹ Megan Eckstein, "ONR Planning First Solid-State Laser Weapon Prototypes On DDG, LCS," *Inside the Navy*, August 20, 2012. Ellipse in the quote as in the article.

work on directed energy technologies in PE 0602114N. The Navy's FY2014 budget describes the proposed work in this area as follows:

Title: DIRECTED ENERGY

Description: The goal of this activity is to develop Directed Energy (DE) technology for Navy applications. The DE program addresses the requirements of future Navy combatants to provide ship defense against the emerging threats that are proliferating throughout the Navies of the world. The Directed Energy portion of this activity consists of two elements. The first element involves applied research and development of technologies supporting advanced accelerators with applications to directed energy weapons. This activity also includes the Free Electron Laser (FEL) Innovative Naval Prototype (INP) which will deliver multimission capability....

[The] FY 2013 to FY 2014 increase in funding [from \$31.7 million to \$40.4 million] is due to increased work on the Solid State Laser (SSL) program.

FY 2012 Accomplishments:

Directed Energy and Accelerator Research:

-Continue cryomodule and FEL component development at the FEL testing and integration facility.

-Continue investigation into the application of FEL technology to other areas including advanced materials, optics, bioscience, medical, manufacturing, weaponization, and solid state physics.

-Continue 1 micron filamentation, halo limitation, and short Rayleigh range studies.

-Continue testing of Radio Frequency (RF) gun High Voltage Power Supply (HVPS) components which are required for the 100kW high current injector.

-Continue applied directed energy and accelerator research in: Compton radiation scattering, multiple dielectric thin film coatings, bunch characteristics of electron beam emittance, high grade electromagnetic field generators, electron beam lattice configuration, novel electron beam generation, novel high flux subatomic particle emission, high gain photonic amplification, fundamental power efficiency conversion.

-Continue the development of physics based models for: characterization of subatomic particle interaction and propagation and modeling for validation of photon control structures.

-Continue development of components required for the successful testing of the 100 kW FEL, to support the scale up of the 100 kW FEL into a megawatt class weapon, and to reduce the overall footprint of the system to support the eventual ship integration of the FEL, including normal conducting and super conducting RF electron beam injectors, advanced high power cathode technologies, high power compact amplifiers, and advanced mirrors, coatings and optical components capable of handling the significantly higher energies that are present in a 100 kW level FEL.

-Complete execution of Phase 1B of 100 kW FEL demonstration program.

-Initiate Phase II of the 100 kW FEL program. Phase II will include the fabrication, integration, and acceptance testing of a 100 kW FEL system.

Applied Electromagnetics for High Power Weapons:

-Continue a program to conduct applied research into applied electromagnetics as it relates to lasers, high power microwaves, and advanced sensors for Directed Energy Weapons.

-Initiate the development of Gallium Nitride as an advanced nonlinear optic material.

FY 2013 Plans:

Directed Energy and Accelerator Research:

-Continue all efforts of FY 2012 unless completed above.

Applied Electromagnetics for High Power Weapons:

-Continue the development of Gallium Nitride as an advanced nonlinear optic material.

-Complete applied research into applied electromagnetics as it relates to lasers, high power microwaves, and advanced sensors for Directed Energy Weapons.

Solid State Laser - Technology Maturation (SSL-TM):

-Initiate the development of technologies suitable for a solid state laser weapon system, including technologies for maritime beam director, targeting and laser subsystems, which are capable of supporting future Navy missions to defeat small boat swarms, UAV swarms, and provide potential ISR disruption and/or defeat. This work supports future prototype developments and will include laser subsystem (potentially both slab and fiber solid state systems) and required beam director scientific studies. The focus of the effort will be to support the development and advancement of future Navy Solid State Laser prototypes, including the development of lethality studies and atmospheric characterization. These scientific studies are critical to understand and support missions identified for a layered defensive capability, in the maritime environment, which shall include robust modeling and simulation of atmospheric absorption and turbulence.

-Initiate and conduct lethality testing for notional designs of proposed solid state laser designs. This will include scientific studies of laser erosion, pitting, and ablation of various target materials for improved modeling and simulation, that will support development of the governing technical requirements for a beam director and targeting system capable of performing Navy surface ship self defense missions.

-Initiate and conduct studies of atmospheric absorption and turbulence, suitable for use to evaluate notional maritime beam director subsystems, and shall include studies in adaptive optics for improved lethality performance in low altitude, maritime surface conditions. These scientific studies are critical to understanding the impact of boundary layer and sea-water-air turbulent mechanics on future laser weapons systems and interfaces.

-Initiate and conduct trade studies on innovative solid state laser subsystems designs, based off industry available technologies or those technologies which are supported through planned investments by the High Energy laser Joint Technology Office (HEL JTO). These investments will be considered "break through" type of investments, which require additional scientific study to determine their potential for near term capability improvements in a future naval prototype system.

-Initiate and conduct scientific studies on laser subcomponents, including laser pump diodes and laser gain media, which have the potential to support future acquisition programs, but are based in a solid state laser technologies. Efforts in this area will focus on emerging commercial technologies and government sponsored research, which are suitable for use in a maritime domain. Research and technology developments will include advancements suitable for use by either solid state slab or solid state fiber optic laser subsystems - and which if matured, would enable rapid scientific advancements and improve specific systems performance in identified key performance parameters.

-Initiate and conduct scientific trade studies of notional predictive avoidance systems, which examine the control interfaces between sensors and future prototypical naval laser weapons, which would provide an inherent “safe-arm” function for the projecting of laser power at long range (potentially beyond typical visible, line of sight distances.) Of particular concern is the designs for safety in future laser weapons to halt laser energy propagation, while performing Navy surface ship self defense missions, and avoid inadvertent illumination of non-threat forces (e.g. friendly sensors or platforms.)

FY 2014 Plans:

Directed Energy and Accelerator Research:

-Continue all efforts of FY 2013.

Applied Electromagnetics for High Power Weapons:

-Continue all efforts of FY 2013 unless completed above.

Solid State Laser - Technology Maturation (SSL-TM):

-Continue all efforts of FY 2013.

-Initiate land based testing and evaluation of SSL Advanced Beam Director prototypes which have been ruggedized and suitable for long term exposure to a maritime environment as will be seen by naval combatants.⁶⁰

Issues for Congress

Program of Record and Roadmap

Although the Navy is developing laser technologies and prototypes of potential shipboard lasers, has a generalized vision for shipboard lasers (see “Navy Surface Fleet’s Generalized Vision for Shipboard Lasers” above), and has established a Naval Directed Energy Steering Group whose objectives include the development of a directed energy roadmap (see “Naval Directed Energy Steering Group” above), the Navy currently does not have a program of record for procuring a production version of a shipboard laser, or shipboard laser roadmap.

⁶⁰ Department of Defense, *Department of Defense Fiscal Year (FY) 2014 President’s Budget Submission, Navy Justification Book Volume 1 of 5, Research, Development, Test & Evaluation, Navy, Budget Activities 1, 2, and 3*, April 2013, pp. 81-84 [pdf pages 111-114 of 470].

The Navy states that it is taking a measured approach toward the development and implementation of lasers (and other directed energy weapons) that includes, among other things, developing and testing prototype and demonstration lasers and monitoring independent laser experiments performed by commercial firms. Current operational requirements, the Navy states, do not specify shipboard directed energy weapons to address capability gaps. The Navy states that although lasers and other directed-energy weapons offer options for providing required capabilities, a business case for directed energy weapons over traditional kinetic weapons (such as guns and missiles) has not been developed. The Navy states that although it has not performed an analysis of alternatives (AOA) comparing directed energy weapons to traditional kinetic energy weapons, it is continually analyzing its defensive capabilities for effectiveness against current and potential future threats.

One potential issue for Congress is whether the Navy should act now to adopt a program of record for procuring a production version of a shipboard laser. Another potential issue for Congress is when the Navy anticipates completing the directed energy roadmap that is to be developed by the Naval Directed Energy Steering Group, and whether that roadmap should call for installing lasers on specific surface ships by specific dates.

Arguments Against Developing a Roadmap or Program of Record

Observers who are skeptical about having the Navy act now to adopt a program of record for procuring a production version of a shipboard laser and/or a roadmap that calls for installing lasers on specific surface ships by specific dates could argue one or more of the following:

- **Operational requirements and business case.** Current Navy operational requirements do not specify shipboard directed energy weapons to address capability gaps, and the Navy has not developed a business case for directed energy weapons over traditional kinetic weapons (such as guns and missiles). Until these two things change, it would be premature to adopt a program of record for procuring a production version of a shipboard laser or a roadmap that calls for installing lasers on specific surface ships by specific dates.
- **State of development and risk of “rush to failure.”** The current state of development of potential shipboard lasers includes significant unresolved questions about, for example, how far beam power can be scaled up while maintaining or improving beam quality and handling thermal management issues. In light of these questions, committing the Navy now to deploying lasers on specific ships by specific dates would be premature, and could lead to a “rush to failure” in the Navy’s shipboard laser efforts.
- **Flexibility to incorporate advances.** The Navy’s approach of not committing now to installing lasers on specific ships by specific dates is appropriate in light of the rapid rate of advance in SSL technologies in recent years. The Navy’s current approach is a flexible strategy that allows these advances to be folded into the Navy’s effort as they occur, often at little or no cost to the Navy. Committing now to installing lasers on specific ships by specific dates could lock the Navy into a laser design that might quickly be made obsolete by such advances.
- **History of overly optimistic promises on other DOD lasers.** The Navy’s current approach of not committing now to installing lasers on specific ships by

specific dates reflects lessons learned from past DOD laser development efforts, which include promises concerning the potential dates for having lasers enter operational service that later proved to be overly optimistic.

- **Socialization.** The Navy’s current approach allows time for lasers to become properly “socialized” within the Navy—that is, for knowledge of, and comfort with, lasers to become more widespread among Navy personnel. Committing now to installing lasers on specific ships by specific dates could result in lasers being installed on ships before adequate socialization of lasers within the Navy occurs. This could lead to institutional resistance to, and rejection of, lasers by the broader Navy community.

Arguments Supporting Developing a Roadmap or Program of Record

Observers who support having the Navy act now to adopt a program of record for procuring a production version of a shipboard laser and/or a roadmap that calls for installing lasers on specific surface ships by specific dates could argue one or more of the following:

- **Operational requirements and business case.** Current Navy operational requirements documents can be outdated or reflect insufficient familiarity or comfort with a new technology. Shipboard lasers are caught in a “Catch-22” dilemma traditionally faced by new and different weapon technologies: Operational requirements or a business case for installing shipboard lasers would be best made on the basis of a thorough understanding of the potential uses and value of shipboard lasers, but such an understanding cannot be developed until lasers are installed on ships and used by Navy personnel in various operational settings. In addition, new technologies are often less efficient or less cost effective in their initial versions than they are in later versions, but deploying initial versions can speed up the process of developing follow-on versions that are more efficient or cost effective. Developing a roadmap or program of record could help overcome this dilemma, encourage the Navy to “get off the dime” on procuring and installing shipboard lasers, and prevent shipboard lasers from being perpetually stuck in the research and development stage (i.e., a “technology sandbox”).
- **State of development and risk of “rush to failure.”** Supporters of LaWS believed it was ready for conversion into a program of record. Supporters of MLD argue similarly argue that MLD is ready for conversion into a program of record. A roadmap or program of record can include realistic installation dates that avoid creating a risk of a “rush to failure.”
- **Flexibility to incorporate advances.** A roadmap or program of record can include features that provide flexibility for incorporating technology advancements as they occur. DOD’s approach of evolutionary acquisition with spiral development, which DOD adopted in 2001 as its standard acquisition approach, is intended to permit this.⁶¹

⁶¹ See CRS Report RS21195, *Evolutionary Acquisition and Spiral Development in DOD Programs: Policy Issues for Congress*, by Gary J. Pagliano and Ronald O'Rourke.

- **History of overly optimistic promises on other DOD lasers.** The best way to overcome the history of overly optimistic promises on DOD laser-development efforts is to develop, adopt, and successfully implement a roadmap or program of record for installing lasers on specific ships by specific dates that includes realistic goals for the capabilities of the lasers to be installed and realistic installation dates.
- **Socialization.** The best way to socialize shipboard lasers within the broader Navy community is to install them on Navy ships and permit Navy personnel to use them. As long as lasers remain primarily in the research and development arena, socialization of lasers among the boarder Navy community will occur slowly, if at all.

Past studies on military lasers in general, including potential shipboard lasers, include comments bearing on the above debate. A 2005 Northrop paper, for example, stated:

Despite these technical advances in laser weapons, much of the military operational community remains unaware of their potential. Numerous discussions with serving officers at seminars, conferences and wargames over the past several years indicate that understanding of the current state of progress in laser weapons is mostly limited to the scientific and technical communities. Beyond that, even the leading thinkers and writers of the military operational community have paid scarce attention to laser weapons and their operational implications.... Despite several nascent efforts to understand the military worth of these systems, appreciation of their potential throughout the military operational community remains low.⁶²

The paper also stated:

Solid-state and free-electron laser weapons, adding to the range of laser weapons capabilities, may be less than a decade away. Meanwhile, the personnel who will make key decisions on the development, acquisition and employment of these systems are already half-way or more through their military careers but most have developed little awareness of the potential implications of laser weapons.⁶³

⁶² Richard J. Dunn, III, *Operational Implications of Laser Weapons*, Northrop Grumman Analysis Center Papers, September 2005, p. 9.

⁶³ Richard J. Dunn, III, *Operational Implications of Laser Weapons*, Northrop Grumman Analysis Center Papers, September 2005, p. 24. The paper also stated on page 5:

The challenge to the U.S. military is that our understanding of laser weapons technologies is outpacing efforts to bring these capabilities into the force. Available funding for laser weapons development lags behind what would be necessary to bring technologies to maturity as quickly as possible. Equally threatening to the success of laser weapons in the field is the lack of attention to concept development for laser weapons operational employment. This situation is neither new nor unique to laser weapons. Historically, technical development of new warfighting capabilities – everything from ironclad warships, to heavier-than-air aircraft, to tanks, radar and radar-defeating “stealth” – has proceeded faster than military forces can adapt their warfighting approaches to incorporate the full advantage of the new capability.

Unfortunately, this imbalance frequently means that weapons developers move along at great speed in designing advanced systems with tremendous battlefield potential, but they do so in splendid intellectual isolation. Lacking the guiding hand of operational requirements, they are unable to properly prioritize resources or focus on the weapons capabilities that are most important to warfighters. They can waste precious time and resources pursuing weapons capabilities of lesser operational utility while foregoing development of those that might truly provide a decisive

(continued...)

The chairman of the Defense Science Board (DSB), in a cover memorandum to a 2007 DSB task force report on directed energy weapon systems and technology applications, stated: “Even after many years of development, there is not a single directed energy system fielded today, and fewer programs of record exist today than in 2001. This circumstance is unlikely to change without a renewed focus on this important area.”⁶⁴ The co-chairs of the task force, in their own cover memorandum to the report, stated that

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 higher energy laser capability. The lack of progress is a result of many factors from unexpected technical 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.⁶⁵

The task force’s report states that

The most fundamental issue affecting priority for developing and fielding laser and microwave/millimeter system useful to combatant command missions is the need for cost-benefit analyses supporting priority choices....

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....

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 [Air Force] Airborne Laser—with emphasis [in that program] on a currently unproven mission capability of boost phase intercept of ballistic missiles.⁶⁶

The report also states:

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

(...continued)

advantage. Just as sadly, military forces can field an expensive and promising new capability that remains underutilized because warfighters do not fully understand how to employ it to its greatest advantage. In today’s fast-changing threat environment, given tight Defense resources and the exciting possibilities offered by development of laser weapons, the U.S. cannot afford the wasted time or resources of such mistakes in developing one of the next breakthrough technologies.

⁶⁴ Cover memorandum dated November 26, 2007, from William Schneider, Jr., DSB Chairman, to the Under Secretary of Defense for Acquisition, Technology, and Logistics, transmitting the final report of the Defense Science Board task force on directed energy weapon systems and technology applications.

⁶⁵ Undated cover memorandum from General Larry D. Welch and Dr. Robert J. Hermann, Co-Chairs, to the Chairman, Defense Science Board, transmitting the final report of the Defense Science Board task force on directed energy weapon systems and technology applications.

⁶⁶ [Report of] *Defense Science Board Task Force on Directed Energy Weapons*, Washington, December 2007, pp. ix-x.

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 [weapons] 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....⁶⁷

A 2009 paper on battlefield directed-energy weapons from the Center for Strategic and Budgetary Assessments (CSBA) states:

[H]istorically, the US military has often been slow to identify, adequately prioritize, and respond effectively to the emerging challenges likely to impose the greatest stresses on our forces in future contingencies....

Insofar as directed-energy weapons do not address current operational problems such as combating insurgents and terrorists in Iraq or Afghanistan, and to the extent that they promise to disrupt ways of fighting with which the US military Services are comfortable or to threaten dominant subcultures within these institutions, there may be considerable resistance to this new class of weaponry from the warfighters.⁶⁸

The paper also states:

CSBA's analysis of the prospects for achieving a 2018 IOC [Initial Operational Capability] [for battlefield lasers] has ascertained that a significant number of perceptual, fiscal, operational and institutional obstacles would have to be addressed before fielding is likely to take place. To begin with, there is a history of unfulfilled promises regarding high-energy laser (HEL) technologies from the directed energy community that extends back to the 1970s. The danger, of course, is that this poor past performance could lead decision-makers to downplay or ignore recent advances in laser technologies that, if pursued, could finally yield battlefield applications.⁶⁹

⁶⁷ [Report of] Defense Science Board Task Force on Directed Energy Weapons, Washington, December 2007, pp. 47-48.

⁶⁸ Thomas Ehrhard, Andrew Krepinevich, and Barry Watts, "Near-Term Prospects for Battlefield Directed-Energy Weapons," Washington, Center for Strategic and Budgetary Assessments, January 2009, pp. 3 and 4.

⁶⁹ Thomas Ehrhard, Andrew Krepinevich, and Barry Watts, "Near-Term Prospects for Battlefield Directed-Energy Weapons," Washington, Center for Strategic and Budgetary Assessments, January 2009, p. 3.

Number of Laser Types to Continue Developing

Potential Strategies

A second potential issue for Congress is how many of the three laser types discussed in this report—fiber SSLs, slab SSLs, and FELs—the Navy should continue developing.

Supporters of stopping development of all three types (or of continuing development of one type) might argue that continuing the development of shipboard lasers (or of more than one type of laser), while perhaps desirable, would reduce funding for more important Navy program priorities below critical levels, particularly in a situation of constrained Navy resources. They might argue that the Navy's kinetic weapons in coming years will have sufficient (or largely sufficient) capability for countering the kinds of targets that shipboard lasers could counter.

Supporters of continuing development of two or three types might argue that it would permit continued competition between laser types and provide a hedge against the failure of one of the development efforts. DOD in the past, they might argue, has sometimes pursued comparable programs concurrently to ensure the best outcome for an area of effort deemed important. They might also argue that the Navy's kinetic weapons in coming years will be insufficient to counter certain kinds of targets, or that shipboard lasers would counter them more cost effectively.

Relative Merits of Laser Types

In considering which laser types to continue developing, policymakers may consider the relative merits of each type. Below are some arguments relating to the relative merits each type. The discussions below are intended as introductory only; a full comparison of their relative merits would entail much longer discussions.

Some Arguments Relating to Fiber SSLs

Supporters of LaWS argue that it has a demonstrated ability to counter certain targets of interest at short (but tactically useful) ranges in a marine environment; that it can be installed on Navy ships in the near term; that it promises to be less expensive than a slab SSL; that it poses less of a challenge in terms of thermal management than a slab SSL; that it has less ship impact than FELs; that it uses an industrial laser technology with high reliability and few alignment optics, making possible a simplified system engineering solution for a Navy laser system; and that its power can be scaled up to 100 kW or perhaps more. They argue that the system's BQ, though not excellent, is good enough to disable targets of interest at short ranges. They argue that the system's light wavelength of 1.064 microns, though not exactly on the atmospheric transmission "sweet spot" located at 1.045 microns, is good enough in terms of atmospheric transmission to permit the laser to disable targets of interest at tactically useful ranges, and that development work is underway on SSLs that would emit light at wavelengths above the threshold (about 1.5 microns) at which laser light becomes much less dangerous to human eyes.

Some skeptics of LaWS, including supporters of the MLD, argue that the LaWS's BQ limits its effective range. Other skeptics of LaWS, including supporters of FELs, argue that LaWS's operating wavelength limits its effective range, particularly when compared to FELs, whose wavelengths can be tuned to exactly match atmospheric transmission sweet spots, and that

LaWS's current wavelength is dangerous to human eyes, whereas an FEL can operate at wavelengths matching atmospheric sweet spots that are located above 1.5 microns.

Some Arguments Relating to Slab SSLs

Supporters of MLD argue that it has a demonstrated power level of 105 kW (more than three times that of LaWS); that it has a much better BQ than LaWS, permitting it to counter targets at greater ranges (thereby providing a larger defended area around the ship, and more time to counter targets approaching the ship); that it could be ready for installation on ships as soon as, or not very long after, the LaWS system would be; that a production version could have a procurement cost comparable to, or even less than, that of a production version of LaWS; that the challenge slab SSLs pose in terms of thermal management, though perhaps greater than that of fiber SSLs, can nevertheless be handled; and that slab SSLs can be scaled up to 300 kW or more while retaining good BQ. The MLD contract, they argue, was competitively awarded, that the competitors for the contract included fiber SSLs, and that the contract was awarded instead to a slab SSL.

Supporters of slab MLDs argue that the difference in complexity between fiber SSLs and slab SSLs is not as great as some supporters of LaWS contend—that fiber SSLs, for example, have more free-space optics⁷⁰ than slab SSLs. Supporters of MLD argue that the industrial environments in which commercial fiber SSLs have operated are not characterized by shocks or high humidity—two features that characterize the shipboard operating environment—whereas MLD was designed from the start with eventual ship operations in mind. Supporters of MLD argue that it can be maintained easily in the field through the use of sealed line replaceable units (LRUs).⁷¹ MLD supporters argue, as do supporters of LaWS, that the system has less ship impact than an FEL; that the system's light wavelength of 1.064 microns, though not exactly on the atmospheric transmission "sweet spot" located at 1.045 microns, is good enough in terms of atmospheric transmission to permit the laser to disable targets of interest at tactically useful ranges, and that development work is underway on SSLs that would emit light at wavelengths above the threshold (about 1.5 microns) at which laser light becomes much less dangerous to human eyes.

Skeptics of MLD, including supporters of LaWS, argue that it uses complex optics, making it more expensive to procure and potentially less reliable and more difficult to maintain than LaWS. Other skeptics of MLD, including supporters of FELs, argue, as they do regarding LaWS, that MLD's operating wavelength limits its effective range, particularly when compared to FELs, whose wavelengths can be tuned to exactly match atmospheric transmission sweet spots, and that MLD's current wavelength is dangerous to human eyes, whereas an FEL can operate at wavelengths matching atmospheric sweet spots that are located above 1.5 microns.

⁷⁰ Free space optics are those arranged so that the light travels from one optical element (such as a mirror) to another, with an air gap (i.e., free space) in between.

⁷¹ LRUs are sealed, box-like containers enclosing many of a weapon's components. LRUs support a modular approach to maintenance in which personnel repair the weapon by removing a faulty LRU and replacing it with another.

Some Arguments Relating to FELs

Supporters of FELs argue that unlike SSLs, FELs clearly can be scaled up to megawatt power levels that would be capable of countering a wide range of targets, including supersonic ASCMs and ballistic missiles, and that unlike SSLs, FELs can be scaled up in power from 10 kW to 1 MW without any increase in the size of the system or need for a beam combiner (a component that adds to system complexity and cost). Supporters of FELs argue that in contrast to the fixed wavelength of light emitted by an SSL, the wavelength of light emitted by an FEL can be tuned to exactly match various atmospheric transmission sweet spots, including those above the threshold (about 1.5 microns) at which laser light becomes much less dangerous to human eyes. They also argue that in contrast to SSLs, FELs pose no large thermal management issues because an FEL's waste heat is not produced inside the laser mechanism itself.

Skeptics of FELs, including supporters of SSLs, argue that FELs will not be ready for installation on ships for a significant number of years. They argue that FELs are so large that they cannot be incorporated into most if not all existing Navy ship designs, limiting the potential applicability of FELs to the surface fleet for many years, and that incorporating an FEL into a new ship design could make the ship considerably larger, adding to the ship's construction cost. They also argue that the need for isolating the FEL system from vibration and shock and the possible need for using cryogenic equipment adds to an FEL's cost and complexity.

Implications for Ship Design and Acquisition

Another potential issue for Congress are the possible implications that shipboard lasers might have for the design and acquisition of Navy ships, including the Flight III DDG-51 destroyer that the Navy wants to begin procuring in FY2016.⁷² The ability of existing Navy ship designs to support lasers, particularly in terms of having sufficient electrical power and cooling capacity, can be summarized as follows:

- The Navy has concluded that its Aegis cruisers and destroyers (i.e., CG-47 and DDG-51 class ships), as well as San Antonio (LPD-17) class amphibious ships, would have enough available electrical power under battle conditions (i.e., when many other systems are also drawing electrical power) to support a LaWS system. An August 2010 press report stated: "Today's warships have enough power to support a 100-kilowatt laser, said [Capt. David Kiel, program manager for directed energy and electric weapons at Naval Sea Systems Command]. Any surface combatant large enough to accommodate the close-in weapon system [CIWS] could also carry the fiber laser, he added."⁷³
- Some Navy ships might be able to support, under battle conditions, an SSL with a power *somewhat* above 100 kW.
- No existing Navy surface combatant designs have enough electrical power or cooling capacity to support an SSL with a power level *well* above 100 kW.

⁷² For more on the Flight III DDG-51, see CRS Report RL32109, *Navy DDG-51 and DDG-1000 Destroyer Programs: Background and Issues for Congress*, by Ronald O'Rourke.

⁷³ Grace V. Jean, "Navy Aiming for Laser Weapons at Sea," *National Defense*, August 2010, accessed online at <http://www.nationaldefensemagazine.org/archive/2010/August/Pages/NavyAimingforLaserWeaponsatSea.aspx>.

- Because of its probable size, an FEL could not be backfitted onto existing cruisers or destroyers. Aircraft carriers and “large-deck” amphibious assault ships (i.e., LHA/LHD-type amphibious ships) might have enough room to accommodate an FEL, but existing carriers and amphibious assault ships might not have enough electrical power to support a megawatt-class FEL. In addition, because of thermal blooming and the status of carriers and amphibious assault ships as potential high-value targets, it might make more operational sense to install megawatt-class FELs on ships other than carriers or amphibious assault ships.⁷⁴

The above points suggest that the Navy in coming years could face significant ship-design constraints in its ability to install shipboard lasers, particularly SSLs well above 100 kW in power, and FELs in general. These constraints are a product, in part, of the Navy’s termination of the CG(X) cruiser program, because the CG(X) could have been designed to support SSLs well above 100 kW in power and/or a megawatt-class FEL.⁷⁵ Following the termination of the CG(X) program, the Navy has no announced plans to acquire a surface combatant clearly capable of supporting an SSL well above 100 kW in power, or an FEL.

Ship-design options for expanding the Navy’s ability to install lasers on its surface ships in coming years include the following:

- design the new Flight III version of the DDG-51 destroyer, which the Navy wants to start procuring in FY2016, with enough space, electrical power, and cooling capacity to support an SSL with a power level of 200 kW or 300 kW or more—something that could require lengthening the DDG-51 hull, so as to provide room for laser equipment and additional electrical generating and cooling equipment;
- design and procure a new destroyer as a follow-on or substitute for the Flight III DDG-51 that can support an SSL with a power level of 200 kW or 300 kW or more, and/or a megawatt-class FEL;⁷⁶
- modify the designs of amphibious assault ships to be procured in coming years, so that they can support SSLs with power levels of 200 kW or 300 kW or more, and/or megawatt-class FELs; and
- modify the design of the Navy’s new Ford (CVN-78) class aircraft carriers, if necessary, so that they can support SSLs with power levels of 200 kW or 300 kW or more, and/or megawatt-class FELs.⁷⁷

⁷⁴ The issue of thermal blooming in “down-the-throat” engagements is of particular concern for a megawatt-class laser. Since carriers and amphibious assault ships are potential high-value targets for an attacker, it might make more operational sense to install megawatt-class FELs on ships other than carriers or amphibious assault ships, so that those other ships could use their FELs to counter targets that are flying a crossing path toward a carrier or amphibious assault ship.

⁷⁵ For more on the CG(X) program, see CRS Report RL34179, *Navy CG(X) Cruiser Program: Background for Congress*, by Ronald O’Rourke.

⁷⁶ For more on the option of a new-design destroyer, see CRS Report RL32109, *Navy DDG-51 and DDG-1000 Destroyer Programs: Background and Issues for Congress*, by Ronald O’Rourke.

⁷⁷ For more on the CVN-78 program, see CRS Report RS20643, *Navy Ford (CVN-78) Class Aircraft Carrier Program: Background and Issues for Congress*, by Ronald O’Rourke.

An April 29, 2013, press report states:

Now that the U.S. Navy is pushing even harder to equip its vessels with lasers, the service is focusing on reliable, high-voltage shipboard power to feed those weapons. Indeed, Navy officials say, meeting that need is becoming a matter of national security.

“The work being done in this area is vital,” said Thomas Killion, who heads the Office of Naval Research’s (ONR’s) Office of Transition, during this month’s Electric Ship Technologies Symposium outside Washington. “As the upcoming deployment of a shipboard laser weapon reminds us, we need power generation and power management systems with greater-than-ever capabilities, but from devices that are smaller than ever.”...

Now, navy scientists are looking for ways to better power those shipboard weapons. ONR-supported efforts are focused on cutting-edge technologies that include silicon carbide (SiC)-based transistors, transformers and power converters. “SiC is important because it improves power quality and reduces size and weight of components by as much as 90 percent,” says Sharon Beerman-Curtin, ONR’s power and energy science and technology lead. “This is a critical technology enabler for future Navy combatant ships that require massive amounts of highly controlled electricity to power advanced sensors, propulsion and weapons such as lasers and the electromagnetic railgun.”⁷⁸

Options for Congress

Options for Congress regarding potential shipboard lasers include, among other things, the following:

- approve, reject, or modify the Navy’s funding requests for development of potential shipboard lasers;
- request additional information from the Navy and DOD about potential shipboard lasers, perhaps by holding one or more hearings on the issue, or by requiring the Navy to submit one or more reports to Congress on the topic;
- encourage or direct the Navy or some other DOD organization to perform an analysis of alternatives (AOA) comparing the cost-effectiveness of lasers and traditional kinetic weapons (such as guns and missiles) for countering surface, air, and missile targets;
- encourage or direct the Navy to adopt a program of record for procuring a production version of a shipboard laser, and/or a roadmap that calls for installing lasers on specific surface ships by specific dates;
- review and comment on any roadmap for shipboard lasers that the Navy adopts;
- in the absence of a Navy program of record or roadmap, direct the Navy to develop and install lasers with certain capabilities on a certain number of Navy surface ships by a certain date;⁷⁹

⁷⁸ Michael Fabey, “U.S. Navy Beefing Up Shipboard Power For Laser Weapon Needs,” *Aerospace Daily & Defense Report*, April 29, 2013: 4.

⁷⁹ This option could take the form of a provision broadly similar to Section 220 of the FY2001 defense authorization act (H.R. 4205/P.L. 106-398 of October 30, 2000), which set goals for the deployment of unmanned combat aircraft (continued...)

- encourage or direct the Navy to design the Flight III version of the DDG-51 destroyer so that it can support an SSL with a power level of 200 kW or 300 kW or more;
- encourage or direct the Navy to design and procure a new destroyer as a follow-on or substitute for the Flight III DDG-51 that can support an SSL with a power level of 200 kW or 300 kW or more, and/or a megawatt-class FEL;
- encourage or direct the Navy to modify the designs of amphibious assault ships to be procured in coming years, so that they can support SSLs with power levels of 200 kW or 300 kW or more, and/or megawatt-class FELs; and
- encourage or direct the Navy to modify the design of the Navy's new Ford (CVN-78) class aircraft carriers, if necessary, so that they can support SSLs with power levels of 200 kW or 300 kW or more, and/or megawatt-class FELs.

Legislative Activity for FY2014

FY2014 Funding Request

The Navy's proposed FY2014 budget requests \$40.4 million for research and development work on directed energy technologies, including the FEL program and SSL technologies. The work forms part of Program Element (PE) 0602114N, Power Projection Applied Research, in the Navy's research and development account.

FY2014 National Defense Authorization Act (H.R. 1960/S. 1197)

House

The House Armed Services Committee, in its report (H.Rept. 113-102 of June 7, 2013) on H.R. 1960, recommends approval of the Navy's FY2014 funding request for PE 0602114N, Power Projection Applied Research, which includes \$40.4 million requested for research and development work on directed energy technologies, including the FEL program and SSL technologies. (Page 427)

Section 222 of the bill as reported by the committee states:

SEC. 222. ESTABLISHMENT OF FUNDING LINE AND FIELDING PLAN FOR NAVY LASER WEAPON SYSTEM.

(a) In General- The Secretary shall ensure that each future-years defense program submitted to Congress under section 221 of title 10, United States Code, that covers any of fiscal years 2018 through 2028 includes a funding line and fielding plan for a Navy laser weapon system with respect to such fiscal years.

(...continued)

and unmanned combat vehicles. For the text of Section 220, see **Appendix K**.

(b) Alternative Report- If the Secretary determines that the technology and maturation efforts of a Navy laser weapon system conducted prior to fiscal year 2016 do not indicate that suitable technology warranting a program of record for such system will be available by 2018, the Secretary may waive the requirements of subsection (a) if the Secretary submits to the congressional defense committees written justification of such determination, including a description of the technical shortcomings of such system, by not later than March 30, 2016.

Regarding Section 222, H.Rept. 113-102 states:

Section 222—Establishment of Funding Line and Fielding Plan for Navy Laser Weapon System

This section would ensure that future defense budgets submitted to Congress for fiscal years 2018–28 include a funding line and fielding plan for a Navy laser weapon system. In the event that the state of the technology does not warrant a program of record, the Secretary of the Navy can waive the requirements of this section by providing written justification for that decision. (Page 106)

The report also states:

Maritime Laser Weapon System

The committee applauds the Navy’s efforts in directed energy research and encourages the continuation of those efforts. The committee is also encouraged by the recent decision to deploy the Laser Weapon System (LaWS) for further testing and evaluation on the USS Ponce, in a stressing maritime environment. The committee believes such operational testing is necessary to work out the technical challenges inherent in directed energy systems, in addition to identifying potential integration and policy challenges that might prove to be impediments to transitioning these types of systems to the fleet. Additionally, the committee recognizes that the Navy is developing other advanced technologies which will present similar integration challenges, in particular with regards to power generation, storage, and delivery. The committee encourages the Navy to begin developing a broadly applicable strategy for addressing these power challenges in order to facilitate technology integration onto naval vessels in the future. Furthermore, the committee directs the Secretary of the Navy to provide a briefing to the Committees on Armed Services of the Senate and the House of Representatives within 90 days after the date of the enactment of this Act on the testing efforts related to the LaWS deployment. The briefing should include:

- (1) An overview of the test campaign plans and success criteria;
- (2) Details of weapon system use and performance;
- (3) A comparison of system performance with conventional weapons systems;
- (4) A discussion of the associated power requirements with a comparison of the anticipated power requirements for other advanced weapons systems; and
- (5) Unforeseen challenges associated with system maintenance and longevity in a maritime environment. (Pages 57-58)

The report also states:

Standardization of directed energy weapon systems characterization

The committee is aware of several research, development, test, and evaluation (RDT&E) programs which pursue the development and eventual deployment of directed energy weapon systems. The committee understands the importance of the services and defense agencies' ability to leverage RDT&E investments whenever possible to maximize the mutual benefit of these investments. Therefore, the committee encourages the services and defense agencies to continue to work synergistically in the development of these systems whenever possible. However, the committee is concerned about the inconsistency of definition of system performance among the different programs which make comparison of technologies and identification of leveraging opportunities between programs difficult. System descriptors such as "beam quality" for laser systems have multiple definitions within the directed energy community at large, and are not directly comparable between different systems. Some descriptors may only be applicable to a limited subset of missions and therefore inhibit the extrapolation of system performance to other missions. The ability to perform such comparisons is vital in the assessment of the different laser technologies applicability for missions of national interest.

Therefore, the committee directs the Secretary of Defense to develop a common set of parameters to describe directed energy weapon system performance with standardized definitions to be employed on all Department of Defense directed energy programs. The committee further directs the Secretary of Defense to submit a report to the Committees on Armed Services of the Senate and the House of Representatives within 12 months after the date of the enactment of this Act, which provides the rationale behind directed energy weapon system performance definitions. (Page 98)

Senate

The Senate Armed Services Committee, in its report (S.Rept. 113-44 of June 20, 2013) on S. 1197, recommends approval of the Navy's FY2014 funding request for PE 0602114N, Power Projection Applied Research, which includes \$40.4 million requested for research and development work on directed energy technologies, including the FEL program and SSL technologies. (Page 335)

S.Rept. 113-44 states:

High energy laser weapons

The committee notes that in the fiscal year 2014 budget request, the Department requested \$364.0 million for high energy laser research and development. One of the key challenges in comparing the performance and maturity levels of the various laser systems across the services, the Defense Advanced Research Projects Agency (DARPA), and the Missile Defense Agency, is the lack of common performance metrics and the criteria that can be used for down-selection, further development, and eventual deployment. To address this deficiency, the Assistant Secretary of Defense for Research and Engineering shall develop a set of common high energy laser metrics that characterize the operational performance of a high energy laser to include a measurement of power deposited on a given area over a given amount of time at a given distance, dependent upon atmospheric conditions, as a function of the size, weight, and power of the complete laser weapon system, including power and thermal management sub-systems, the laser source, the beam control and optical sub-systems, and the command and control sub-systems. These metrics, as well as an evaluation according to these metrics that will be used for decisions on further development and eventual deployment of all current high energy laser systems the Department is currently developing, shall be reported to the congressional defense committees no later than 180 days after the enactment of this Act.

Furthermore, the committee notes that the Department is pursuing multiple programs with solid state fiber lasers and strongly urges the Department to develop an integrated strategy that will lead to a rational down-selection process towards those systems that are most effective and mature in order to accelerate their testing in relevant operational environments and ultimately deployment.

Lastly, the committee notes that the majority of DOD's laser directed energy programs are focused on the development and demonstration of high-average-power continuous wave lasers, which have the goal of delivering sufficient thermal energy to damage or destroy targets. Insufficient attention is being given to ultra-shortpulse very-high-peak-power lasers which can produce unique nonthermal effects on materials, components, and systems—effects which cannot be produced by deposition of thermal energy. The committee notes that other countries are exploring the applications for these non-thermal effects, and are advancing the development of ultra-short-pulse high-peak power lasers and associated technologies. The committee directs the Department, in particular DARPA, to begin considering these systems to determine what military utility they can provide. (Pages 61-62)

FY2014 DOD Appropriations Act (H.R. 2397)

House

The House Appropriations Committee, in its report (H.Rept. 113-113 of June 17, 2013) on H.R. 2397, recommends approval of the Navy's FY2014 funding request for PE 0602114N, Power Projection Applied Research, which includes \$40.4 million requested for research and development work on directed energy technologies, including the FEL program and SSL technologies. (Page 223)

Appendix A. Laser Power Levels Required to Counter Targets

Table A-1 shows two Navy perspectives, a Defense Science Board (DSB) task force perspective, and two industry perspectives on approximate laser power levels needed to affect various categories of targets. As can be seen in the table, these perspectives differ somewhat regarding the power levels needed to counter certain targets, perhaps because of differing assumptions about beam quality (BQ) and other factors.

Table A-1. Approximate Laser Power Levels Needed to Affect Certain Targets

Multiple perspectives that may reflect varying assumptions about BQ and other factors

Source	Beam power measured in kilowatts (kW) or megawatts (MW)				
	~10 kW	Tens of kW	~100 kW	Hundreds of kW	MW
One Navy briefing (2010)	UAVs				
	Small boats				
	Missiles (starting at 500 kW)				
Another Navy briefing (2010)		Short-range operations against UAVs, RAM, MANPADS (50 kW-100kW; low BQ)	Extended-range operations against UAVs, RAM, MANPADS, ASCMs flying a crossing path (>100 kW, BQ of ~2)	Operations against supersonic, highly maneuverable ASCMs, transonic air-to-surface missiles, and ballistic missiles (>1 MW)	
Industry briefing (2010)		UAVs and small boats (50 kW)	RAM (100+ kW), subsonic ASCMs (300 kW), manned aircraft (500 kW)	Supersonic ASCMs and ballistic missiles	
Defense Science Board (DSB) report (2007)		Surface threats at 1-2 km		Ground-based air and missile defense, and countering rockets, artillery, and mortars, at 5-10 km ^a	"Battle group defense" at 5-20 km (1-3 MW)
Northrop Grumman research paper (2005)	Soft UAVs at short range	Aircraft and cruise missiles at short range	Soft UAVs at long range	Aircraft and cruise missiles at long range, and artillery rockets (lower hundreds of kW) Artillery shells and terminal defense against very short range ballistic missiles (higher 100s of kW)	

Source: One Navy briefing: Briefing slide entitled "HEL [High-Energy Laser] Missions," in briefing entitled "Directed Energy Warfare Office (DEWO) Overview," July 23, 2010. **Another Navy briefing:** Briefing slide entitled "Surface Navy Laser Vision," in briefing entitled "Navy Directed Energy Efforts – Ship Based Laser Weapon System," July 23, 2010. **Industry briefing:** Briefing to CRS by an industry firm in the summer of 2010; data shown in table used here with the firm's permission. **DSB report:** [Report of] Defense Science Board Task Force on Directed Energy Weapons, December 2007, Table 2 (page 12). **Northrop Grumman research paper:** Richard J. Dunn, III, Operational Implications of Laser Weapons, Northrop Grumman (Analysis Center Papers), September 2005 (available online at http://www.northropgrumman.com/analysis-center/paper/assets/Operational_Implications_of_La.pdf), visual inspection of Figure 1 (page 7).

Notes: kW is kilowatts; MW is megawatts; km is kilometer; RAM is rockets, artillery, mortars; MANPADS is man-portable air defense system (i.e., shoulder-fired surface-to-air missiles).

- a. Note that this statement refers to ground-based operations. It is not clear how this statement might change for shipboard operations, where atmospheric absorption due to water vapor can be an increased concern.

Appendix B. Navy Organizations Involved in Developing Lasers

Principal Navy organizations involved in developing lasers for potential shipboard use include

- the Office of Naval Research (ONR);
- the Naval Research Laboratory (NRL);
- the Directed Energy and Electric Weapon Systems (DE&EWS) Program Office (PMS-405),⁸⁰
- the Naval Surface Warfare Center (NSWC) Dahlgren Division (NSWCDD), located at Dahlgren, VA; and
- the Directed Energy Warfare Office (DEWO), which the Navy established in August 2009 to serve as an NSWCDD center of excellence.

Additional Navy organizations involved in developing lasers for potential shipboard use include the CIWS program office (PEO IWS 3B, meaning Program Executive Officer, Integrated Warfare Systems, office code 3B); NSWC Crane Division at Crane, IN; NSWC Port Hueneme at Port Hueneme, CA; the Naval Air Weapon Stations at China Lake and Point Mugu, CA, as well as the Naval Air Station Patuxent River, MD, all of which are part of the Naval Air Systems Command (NAVIAR); and the Space and Naval Warfare Systems (SPARWAR) Center Pacific, located at San Diego.

Additional DOD organizations outside the Navy are also involved in developing lasers for potential shipboard use.

⁸⁰ PMS-405 means Project Manager, Shipbuilding, office code 405.

Appendix C. Additional Information on Laser Weapon System (LaWS)

A fiber SSL first uses high power semiconductor laser diodes to convert electricity into light. The light then passes through one or more glass optic fibers that contain a small amount of a deliberately introduced impurity, or “dopant” material, usually ytterbium (Yb). The interaction of the light with the dopant both changes the light’s wavelength (color) and concentrates the light into a narrow laser beam that travels down the fiber until it exits the other end. Special optics combine the output of multiple fibers into one powerful beam. The fibers are referred to as the gain medium, and the laser is called a solid state laser because the gain medium is a solid rather than a liquid (such as in dye lasers) or a gas (as in gas lasers). Over the last decade, dramatic improvements in diodes and fiber materials have enabled a roughly 100-fold increase in the maximum power of an individual fiber SSL, from about 100 watts to about 10 kW.

The Navy’s approach to developing LaWS was to maximize reliance on existing technology and components so as to minimize development and procurement costs. The LaWS prototype incoherently combines light beams from six fiber SSLs—commercial, off-the-shelf (COTS) welding lasers—each with a power of 5.5 kW, to create a laser with a total power of 33 kW⁸¹ and a BQ of 17. The light from the six lasers is said to be incoherently combined because the individual beams are not merged into a true single beam (i.e., the individual beams are not brought in phase with each other). Although the beams are quite close to one another, they remain separate and out of phase with each other, and are steered and focused by the beam director so that they converge into a single spot when they reach the intended target. Coherently combining the six beams into a true single beam (i.e., one in which the six beams are “phase locked”) would require a system with more-complex internal optics and electronic control systems.

LaWS, like many other fiber SSLs, emits light with a wavelength of 1.064 microns, which is close to, but not exactly at, an atmospheric transmission “sweet spot” at 1.045 microns.

LaWS is about 25% efficient, meaning that about 400 kW of ship’s power would be needed to operate a future version of LaWS producing 100 kW of laser light. The remaining 300 kW of electrical energy would be converted into waste thermal energy (heat) that needs to be removed from the system using the ship’s cooling capacity.

The conceptual breakthrough underpinning LaWS was made by scientists at the Pennsylvania State Electronic-Optic Center in 2004 and 2005 during some simple experiments, and by scientists at the Naval Research Laboratory (NRL) in 2006, in detailed analysis and subsequent experiments. Both groups showed that coherently combining light beams was not necessary to create a militarily useful laser from commercial fiber SSLs—that this could be done through the technically simpler approach of incoherently combining their beams.

⁸¹ A June 6, 2010, press report states that “The system uses six commercial off-the-shelf five-and-a-half kilowatt welding lasers....” (Dan Taylor, “Navy Testing Developmental Laser Against Small Surface Vessels,” *Inside the Navy*, June 7, 2010.) Another source puts the total power of LaWS at 32 kW. (Larry Greenemeier, “U.S. Navy Laser Weapon Shoots Down Drones in Test,” *ScientificAmerican.com*, July 19, 2010, accessed online at <http://www.scientificamerican.com/article.cfm?id=laser-downs-uavs>.)

DEWO is the lead system integrator (LSI) and technical direction agent for LaWS. Raytheon, the maker of CIWS, is the prime support contractor for the CIWS integration effort.⁸²

A June 1, 2011, Navy information paper states:

1. The following efforts (funded under Fiscal Year [FY] 2010 Congressional Add) are underway to support the conduct of Trident Warrior (TW) 11 in the June 2011 timeframe:

- Predictive Avoidance – continuing engineering, analysis, software development, and integration of a Predictive Avoidance Safety System (PASS) into the Prototype Laser Weapon System (LaWS)
- Stabilization – continuing engineering, analysis, software development, and integration of Fast Steering Mirrors (FSM) as part of the Beam Control/Tracking subsystem of LaWS
- LaWS KINETO Tracking Mount (KTM) Enclosure – material procurement and enclosure fabrication that will fit within the space constraints of the mechanized landing craft (LCM-8) as a test platform
- TW 11 test planning and documentation development.

Trident Warrior info can be found at:

<http://www.public.navy.mil/usff/tridentwarrior/Pages/default.aspx>

2. The following efforts were accomplished or are underway in support of the PEO IWS Laser Close In Weapon System (CIWS) Draft Weapon Specification development effort :

- Provided: Threat Vulnerability information for both in band and out of band laser engagements; LaWS test results from White Sands Missile Range and St. Nicholas Island ; draft Design Reference Missions (DRMs); draft generic Concept of Operations (CONOPs); system level requirements for multi beam aperture system; draft space, weight, air, power requirements; Laser Trade Study Briefings.
- In Process: Attending System Engineering Working Group (SEWG) meetings in support of Draft Weapon Specification development; providing technical reviews of Draft Weapon Specification developments.

3. The current Technology Readiness Level (TRL) of the Prototype LaWS is approaching 6, based on a system prototype demonstration in a relevant (maritime) environment.⁸³

Figure C-1 shows a picture of the LaWS prototype; **Figure C-2** shows a rendering of LaWS when installed as an addition to a CIWS mount. In **Figure C-2**, the red-colored tube hanging off the left side of the CIWS mount is the LaWS beam director, and the white device bolted to the right side of the CIWS radome is another LaWS component.

⁸² Other firms involved in the LaWS effort include IPG Photonics (the maker of the fiber SSLs), L-3 Communications, and Boeing. The LaWS effort also involves the Pennsylvania State University Electro-Optics Center and the Johns Hopkins University Applied Physics Laboratory.

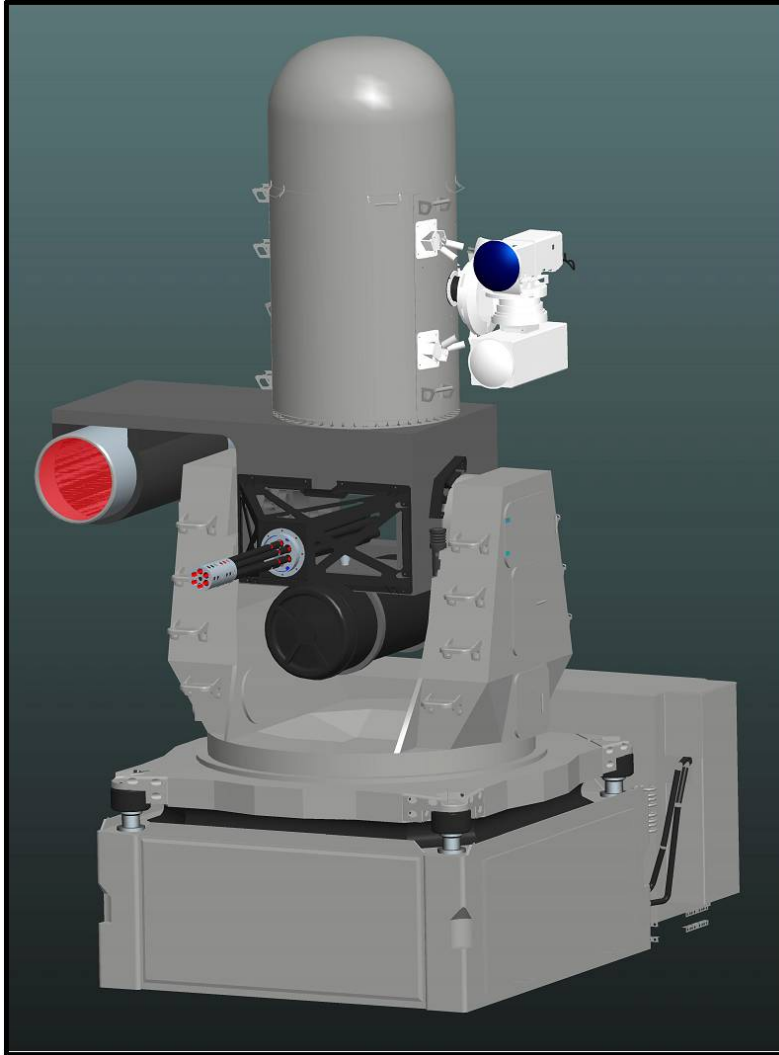
⁸³ Source: Navy information paper dated June 6, 2011, provided by the Navy to CRS and CBO on June 14, 2011.

Figure C-1. Photograph of LaWS Prototype



Source: Photograph provided by Navy Office of Legislative Affairs, November 3, 2010.

Figure C-2. Rendering of LaWS Integrated on CIWS Mount



Source: Rendering provided by Navy Office of Legislative Affairs, November 3, 2010. In this rendering, the red-colored tube hanging off the left side of the CIWS mount is the LaWS beam director, and the white device bolted to the right side of the CIWS radome is another LaWS component.

Appendix D. Additional Information on Tactical Laser System (TLS)

A June 10, 2011, Navy information paper states:

The MK 38 TLS concept is based on a commercial off-the-shelf (COTS) Solid State Laser (SSL) with a simple Beam Director (BD) integrated with the MK 38 Mod 2 Machine Gun System (MGS). Other high energy SSL typically combine several individual beams in order to achieve a higher power output. The TLS is a single phase laser, meaning it does not utilize a combination of several lasers. This does reduce the total power output of the system, but allows for a far greater Beam Quality (BQ). The current BQ is 2.1, but modifications are being made to improve this to 1.5. Beam Quality, along with power output, is a key parameter to determining a laser's effectiveness against targets. With the current BQ and power output, the TLS should be capable of defeating some small boat targets at ranges of up to 2 km, given optimal weather and sea conditions. A future demonstration of the laser system's effectiveness is currently planned in March 2012.

The BD is a simple design with relatively few moving parts. Independent drives enable the TLS to make azimuth corrections faster and point beyond the elevation limits of the MK 38 Mod 2 MGS. The current integration work for the TLS is to have the MK 38 Mod 2 MGS Electro-Optical Sight (EOS) hand track over to the TLS. Track handoff from the EOS to the TLS will be tested in an event scheduled for 29 June 2011 at Eglin Air Force Base.

The TLS is about 30% efficient, meaning 34 kW of power is needed to operate the 10 kW laser. The remaining 24 kW are converted into thermal energy that must be removed from the system. Currently, the TLS will utilize its own power distribution and cooling systems. The power requirement from a ship would be approximately 75 kW, 440 VAC 60 Hz 3 Phase power to run the laser, power management, and currently installed/designed thermal management systems. Additional engineering development would be required for actual shipboard use.

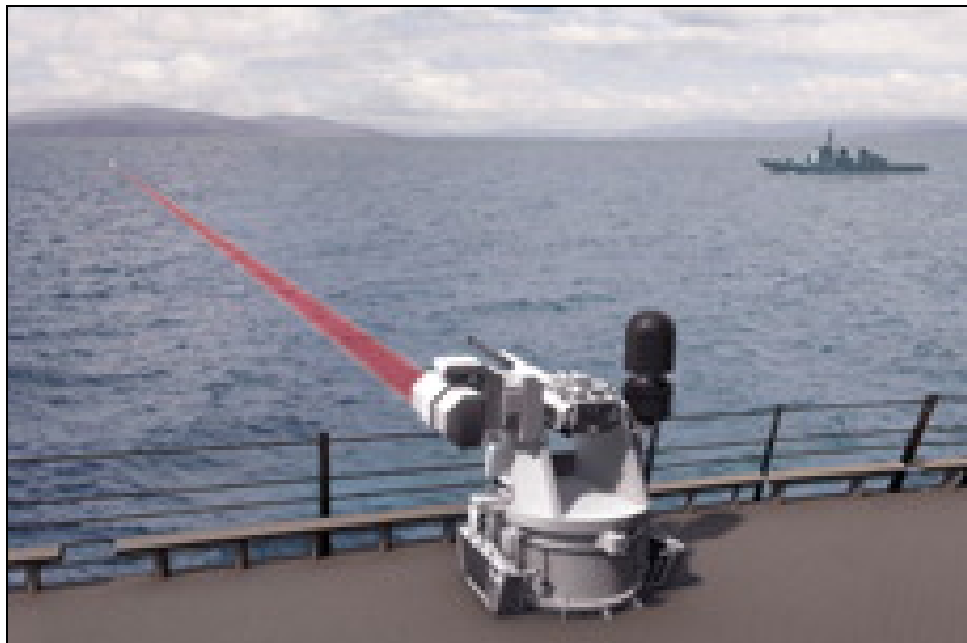
Technical risks identified for the TLS demonstration [include] MGS integration, laser Beam Quality and Beam Director tracking. Accurate target range data is critical to the effectiveness of the TLS. The BD does not include a Laser Range Finder (LRF), and the MK 38 EOS is expected to provide this data. The interface of the EOS and TLS will be tested in June at Eglin as mentioned above. A failure to improve BQ or demonstrate stable tracking for the BD, will impact system effectiveness resulting in reduced range and higher laser dwell times.

IPG is the COTS laser manufacturer. Boeing is the BD designer and Laser Weapons Module lead. The MK 38 system integrator is BAE Systems.⁸⁴

Figure D-1 shows a rendering of TLS when installed as an addition to the Mk 38 machine gun system.

⁸⁴ Navy information paper dated June 10, 2011, provided by the Navy to CRS and CBO June 22, 2011.

Figure D-1. Rendering of TLS Integrated on Mk 38 Machine Gun Mount



Source: BAE news release dated April 7, 2011, entitled “BAE Systems Selected to Demonstrate Tactical Laser System for the U.S. Navy,” accessed online July 5, 2011, at http://www.baesystems.com/Newsroom/NewsReleases/autoGen_1113718157.html

Appendix E. Additional Information on Maritime Laser Demonstration (MLD)

Slab SSLs are similar to fiber SSLs, except that the synthetic crystalline material used as the gain medium is formed into plate-like slabs rather than flexible fibers. Slab SSLs are being developed not just by the Navy, but by other U.S. military services, permitting the Navy to leverage development work funded by other parts of DOD.

MLD coherently combines beams from multiple slab SSLs, each with a power of 15 kW, to create a higher-power beam with a good BQ. Each 15 kW laser is housed in a Line Replaceable Unit (LRU) measuring about 1 foot by 2 feet by 3.5 feet. MLD might be installed on its own mount rather than as an addition to a ship's existing CIWS mount.

MLD, like LaWS, emits light with a wavelength of 1.064 microns, which is close to, but not exactly at, an atmospheric transmission "sweet spot" at 1.045 microns.

Slab SSLs are currently about 20% to 25% efficient, meaning that about 400 kW to 500 kW of a ship's power would be needed to operate a system producing 100 kW of laser light. The remaining 300 kW to 400 kW of electrical energy would be converted into waste thermal energy that needs to be removed from the system using the ship's cooling capacity. Future slab SSLs might have efficiencies of about 30%.

In March 2009, Northrop demonstrated a version of MLD that coherently combined seven slab SSLs, each with a power of about 15 kW, to create a beam with a power of about 105 kW and a BQ of less than 3.⁸⁵

Scaling up a slab laser to a total power of 300 kW and a BQ of 2 is not considered to require any technological breakthroughs. A slab laser with a total power of 300 kW might require a below-deck space measuring roughly 4.5 feet by 8 feet by 12 feet. Supporters of slab SSLs such as MLD believe they could eventually be scaled up further, to perhaps 600 kW. Slab SSLs are not generally viewed as easily scalable to megawatt power levels.

MLD is a commercially integrated weapon system with Northrop and L3-Brashears as the principal contractors. The government test team includes NSWC Dahlgren (VA), NSWC Port Hueneme (CA), and NAWC China Lake (CA). Although Northrop is the primary contractor for MLD, several other firms, such as Raytheon and Textron, are involved in efforts to develop slab SSLs for potential use by U.S. military services.

An April 8, 2011, ONR news release stated:

Marking a milestone for the Navy, the Office of Naval Research and its industry partner on April 6 successfully tested a solid-state, high-energy laser (HEL) from a surface ship, which disabled a small target vessel.

⁸⁵ See Northrop Grumman press release dated March 18, 2009, and entitled "Northrop Grumman Scales New Heights in Electric Laser Power, Achieves 100 Kilowatts From a Solid-State Laser," accessed online at http://www.irconnect.com/noc/press/pages/news_releases.html?d=161575.

The Navy and Northrop Grumman completed at-sea testing of the Maritime Laser Demonstrator (MLD), which validated the potential to provide advanced self-defense for surface ships and personnel by keeping small boat threats at a safe distance.

“The success of this high-energy laser test is a credit to the collaboration, cooperation and teaming of naval labs at Dahlgren, China Lake, Port Hueneme and Point Mugu, Calif.,” said Chief of Naval Research Rear Adm. Nevin Carr. “ONR coordinated each of their unique capabilities into one cohesive effort.”

The latest test occurred near San Nicholas Island, off the coast of Central California in the Pacific Ocean test range. The laser was mounted onto the deck of the Navy’s self-defense test ship, former USS Paul Foster (DD 964).

Carr also recognized the Office of the Secretary of Defense’s High Energy Joint Technology Office and the Army’s Joint High Powered Solid State Laser (JHPSSL) program for their work. MLD leverages the Army’s JHPSSL effort.

“This is the first time a HEL, at these power levels, has been put on a Navy ship, powered from that ship and used to defeat a target at-range in a maritime environment,” said Peter Morrison, program officer for ONR’s MLD.

In just slightly more than two-and-a-half years, the MLD has gone from contract award to demonstrating a Navy ship defensive capability, he said.

“We are learning a ton from this program—how to integrate and work with directed energy weapons,” Morrison said. “All test results are extremely valuable regardless of the outcome.”

Additionally, the Navy accomplished several other benchmarks, including integrating MLD with a ship’s radar and navigation system and firing an electric laser weapon from a moving platform at-sea in a humid environment. Other tests of solid state lasers for the Navy have been conducted from land-based positions.

Having access to a HEL weapon will one day provide warfighter with options when encountering a small-boat threat, Morrison said.

But while April’s MLD test proves the ability to use a scalable laser to thwart small vessels at range, the technology will not replace traditional weapon systems, Carr added.

“From a science and technology point of view, the marriage of directed energy and kinetic energy weapon systems opens up a new level of deterrence into scalable options for the commander. This test provides an important data point as we move toward putting directed energy on warships. There is still much work to do to make sure it’s done safely and efficiently,” the admiral said.⁸⁶

A June 1, 2011, Navy information paper states:

As part of [ONR’s] Survivability and Self Defense focus area, ONR with NAVSEA Program Executive Office for Integrated Weapons Systems (PEO IWS), the NAVSEA Directed Energy Program Office (PMS-405), the DoD High Energy Laser Joint Technology Office

⁸⁶ Geoff S. Fein, “MLD Test Moves Navy a Step Closer to Lasers for Ship Self-Defense,” April 8, 2011 (Office of Naval Research news release, accessed online at <http://www.onr.navy.mil/en/Media-Center/Press-Releases/2011/Maritime-Laser-MLD-Test.aspx>).

(HEL JTO) and the US Army Space and Missile Development Command (USA/SMDC), contracted with Northrop Grumman to design, develop, integrate, install and test the Maritime Laser Demonstration (MLD) from 2009 until early 2011.

The MLD program's main objective was to demonstrate a ship based laser "proof-of-concept" weapons system to defend against small boat attacks, using commercially available laser and beam director components. The demonstrator showed the system design could be installed and function on existing Navy DDG, CG, LSD, LPD, LHA, LHD, and/or FFG ships; using the ship's power and fire control capabilities, and use advanced solid state laser slab directed energy technologies similar to those used in industrial applications. The successful testing and temporary integration of the MLD on the USS Paul Foster (US Navy Spruance Class test ship) and the acquired experience promotes confidence in the ability to subsequently develop a notional Naval Maritime Laser based Weapon System (NMLWS). The MLD Program marked a significant new naval capability to deter and inhibit an attack by small fast attack boats in a maritime environment.

After testing, the MLD system was removed from the USS Paul Foster and returned to Northrop Grumman facilities in El Segundo, California. The MLD system, as tested, employed a 15 Kilowatt 1.065 micron wavelength laser developed in the OSD HEL JTO Joint High Power Solid State Laser (JHPSSL) program, and on loan from the USA/SMDC. The modified JHPSSL module's output was directed to the target boat and laser fluence on the target was controlled by a motion stabilized beam director. Initial tracking of high speed, remotely operated and maneuverable small boat surface targets was provided by the ship's complement of existing radars, and then passively and actively tracked by the beam director cameras through varying environmental conditions up to World Meteorological Organization (WMO) sea states of three (3). Active engagement of the target was controlled by test, safety and fire controllers on the USS Paul Foster, located in the ship's command center. Significant data collection and photo coverage was gained during testing. In early April of 2011, the Maritime Laser Demonstration program showed significant capabilities for defeating small boats through the defeat of structural elements of the small boat. Additionally, engines on the remotely operated small boat target were later set ablaze by the laser at distances of over one mile. The MLD program marks the first time a laser weapon has been test fired from a US Navy ship, and successfully showed the potential power of a laser weapon system in the maritime environment.

The unclassified and publically released video of the testing of the MLD system may be viewed at YouTubetm at the URL: <http://www.youtube.com/watch?v=awsQs4ct0c4>.⁸⁷

Figure E-1 shows the MLD on a trailer; **Figure E-2** shows a schematic of the system; **Figure E-3** shows a rendering of the beam director for the MLD in a notional shipboard installation.

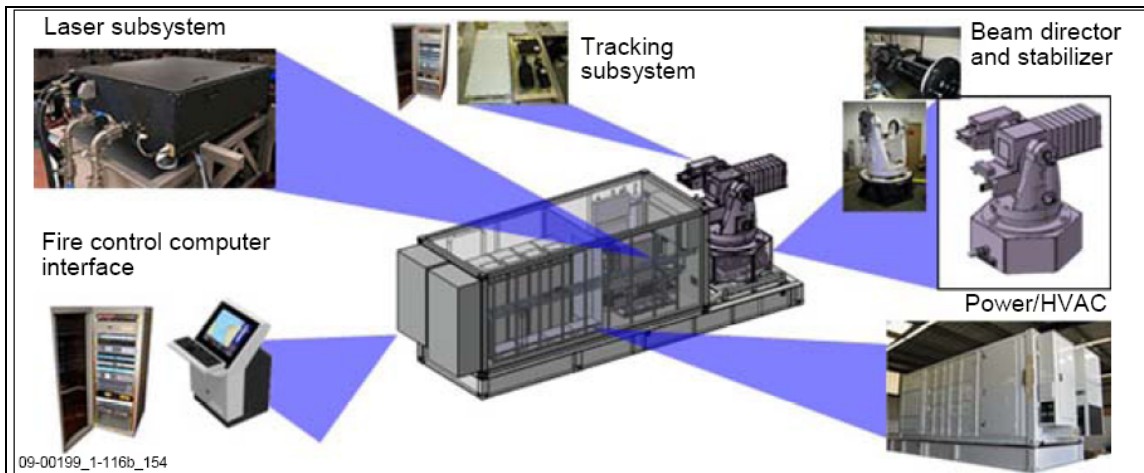
⁸⁷ Source: Navy information paper dated June 1, 2011, provided by the Navy to CRS and CBO on June 14, 2011.

Figure E-1. Photograph of MLD on Trailer



Source: Photograph provided by Navy, November 29, 2010.

Figure E-2. Schematic of MLD



Source: Illustration provided by Navy, November 11, 2010.

Figure E-3. Rendering of MLD in Notional Shipboard Installation



Source: Photograph provided by Northrop, October 21, 2010.

Appendix F. Additional Information on Free Electron Laser (FEL)

An FEL uses an electron gun to generate a stream of electrons. The electrons are then sent into a linear particle accelerator to accelerate them to light speeds. The accelerated electrons are then sent into a device, known informally as a wiggler, that exposes the electrons to a transverse magnetic field, which causes the electrons to “wobble” from side to side and release some of their energy in the form of light (photons). The photons are then bounced between mirrors and emitted as a coherent beam of laser light. To increase the efficiency of the system, some of the electrons are then cycled back to the front of the particle accelerator via an energy recovery loop.⁸⁸

Unlike an SSL, which emits light with a fixed wavelength determined by the composition of its gain medium, an FEL’s components can be adjusted to change the wavelength of light that it emits, so as to match various atmospheric transmission “sweet spots.” The basic architecture of an FEL offers a clear potential for scaling up to power levels of one or more megawatts. A well-designed FEL can in theory be increased in power from 10 kW to 1 MW without an increase in system size, and without need for beam combiners. An FEL emits a beam with a BQ of 1 or close to 1.

Schematics of notional or developmental shipboard FELs today generally show them as devices with a length of roughly 100 feet. An FEL’s ultimate shipboard space requirements will depend in part on how it is integrated into a ship’s design, and whether the FEL uses room-temperature or superconducting particle-acceleration structures. Using superconducting acceleration structures can reduce the length of an FEL, and would require the use of cryogenic equipment to bring the superconducting structures down to the very low temperatures needed to make them superconducting. Operating an FEL would result in the production of X rays, requiring the system to be shielded to protect the ship’s crew and other parts of the ship.

FELs that recycle electrons have an efficiency of about 10%, meaning that about 10 MW of ship’s power would be needed to operate an FEL producing 1 MW of laser light. The remaining 900 kW of electrical energy is converted into waste thermal energy.

The FEL development effort is led by ONR. The effort also includes several other Navy organizations and institutions,⁸⁹ four Department of Energy (DOE) laboratories,⁹⁰ and several

⁸⁸ A 2004 media advisory from the Office of Naval research states:

In the FEL, electrons are stripped from their atoms and then whipped up to high energies by a linear accelerator. From there, they are steered into a wiggler—a device that uses an electromagnetic field to shake the electrons, forcing them to release some of their energy in the form of photons. As in a conventional laser, the photons are bounced between two mirrors and then emitted as a coherent beam of light. However, FEL operators can adjust the wavelength of the laser’s emitted light by increasing or decreasing the energies of the electrons in the accelerator or the amount of shaking in the wiggler.

(Office of Naval Research media advisory released July 30, 2004, and entitled “Free-Electron Laser Reaches 10 Kilowatts,” accessed online at <http://www.onr.navy.mil/Media-Center/Press-Releases/2004/Free-Electron-Laser-10-Kilowatts.aspx>.)

⁸⁹ These include the Naval Postgraduate School in California, the U.S. Naval Academy in Maryland, NRL, NSWC Carderock in Maryland, the Naval Air Weapons Center (NAWC) China Lake in California, NSWCDD, PMS405, and the Naval Warfare Systems Center Pacific (SPAWAR) in California.

universities.⁹¹ Contractors involved in FEL development have included Boeing (CA), Raytheon (MA), SAIC (VA), Niowave (MI), and Advanced Energy Systems (NY). Boeing and Raytheon competed for the contract to design the 100 kW FEL. In September 2010, ONR announced that it had selected Boeing.⁹² The award makes Boeing the Navy's current primary contractor for FEL development.

A January 20, 2011, news report states:

Scientists at Los Alamos National Lab in Los Alamos, N.M., have achieved a remarkable breakthrough with the Office of Naval Research's (ONR) Free Electron Laser (FEL) program, setting the stage for a preliminary design review scheduled Jan. 20-21 in Virginia.

Researchers demonstrated an injector capable of producing the electrons needed to generate megawatt-class laser beams for the Navy's next-generation weapon system Dec. 20, months ahead of schedule.

"The injector performed as we predicted all along," said Dr. Dinh Nguyen, senior project leader for the FEL program at the lab. "But until now, we didn't have the evidence to support our models. We were so happy to see our design, fabrication and testing efforts finally come to fruition. We're currently working to measure the properties of the continuous electron beams, and hope to set a world record for the average current of electrons."

Quentin Saulter, FEL program manager for ONR, said the implications of the FEL's progress are monumental.

"This is a major leap forward for the program and for FEL technology throughout the Navy," said Saulter. "The fact that the team is nine months ahead of schedule provides us plenty of time to reach our goals by the end of 2011."⁹³

A June 1, 2011, Navy information paper states:

In September 2010, Boeing was selected as the lead systems integrator for the critical design phase of the FEL INP to design, develop, integrate and test a 100kW Free Electron Laser demonstration prototype that will be used to study scaling to megawatt level output powers. Boeing successfully completed the Preliminary Design Review in January 2011 and is working on the critical design of the 100kW demonstration prototype.

The Navy's goal is to build a megawatt-class free electron laser that due to its flexibility in operating at multiple wavelengths has more capability than any other HEL weapon system to operate in any maritime environment in the world. Its all electric nature and multimission

(...continued)

⁹⁰ These are the Thomas Jefferson National Laboratory in Virginia, the Los Alamos National Laboratory in New Mexico, the Brookhaven National Laboratory in New York, and the Argonne National Laboratory in Illinois.

⁹¹ These include the MIT Lincoln Laboratory in Massachusetts, Vanderbilt University in Tennessee, Colorado State University, the University of California, the University of Wisconsin, Stanford University in California, Yale University in Connecticut, the University of Texas, and the University of Maryland.

⁹² See Department of Defense contract announcement No. 804-10, dated September 7, 2010, accessed online at <http://www.defense.gov/contracts/contract.aspx?contractid=4361>. See also Geoff Fein, "ONR Awards Boeing \$23 Million To Finish Free Electron Laser Design," *Defense Daily*, September 17, 2010: 3-4.

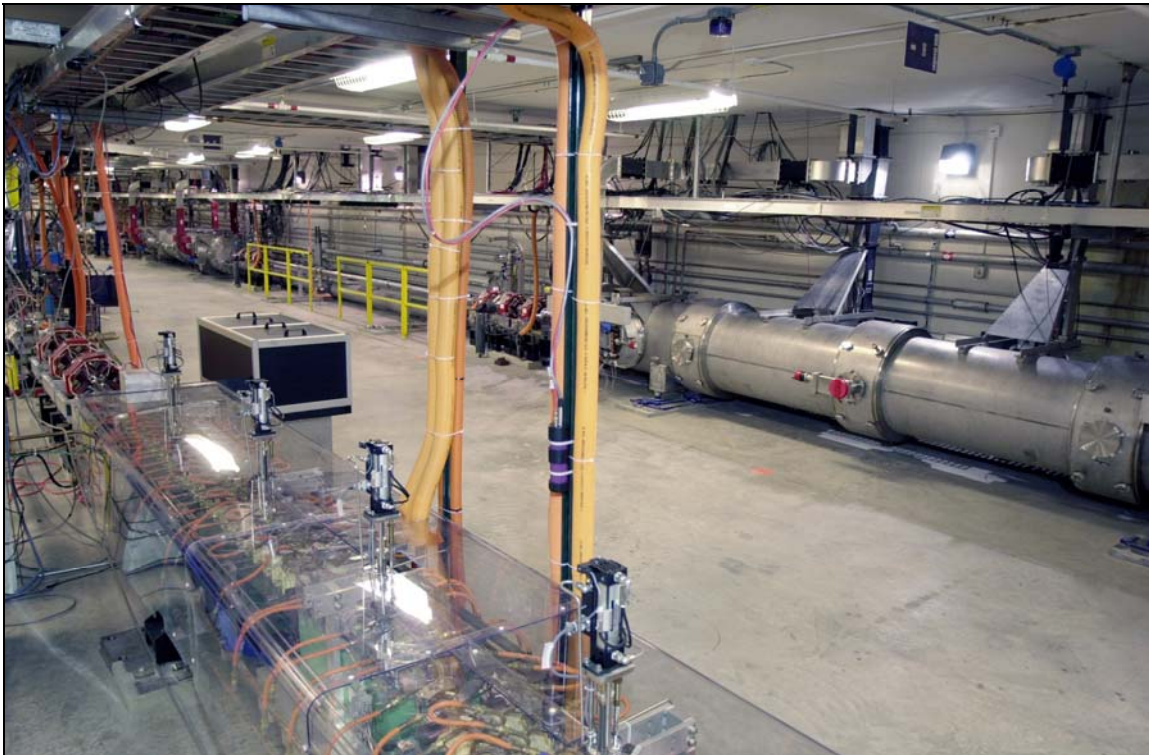
⁹³ Rob Anastasio, "Office of Naval Research Achieves Milestone in Free Electron Laser Program," *Navy News Service*, January 20, 2011.

capability could reduce the cost and logistics burden for the Navy. Presently the FEL program is the only peer-reviewed electric laser megawatt class program in DoD.⁹⁴

A March 21, 2012, press report stated that the FEL project was undergoing critical design review (CDR) that week.⁹⁵ A March 26, 2012, press report stated that “Boeing made good progress maturing the megawatt free electron laser, as shown during its critical design review....” The report stated: “[Roger] McGinnis, [program executive for INPs at ONR’s Naval Air Warfare and Weapons Department], said that the optics was likely the most challenging part but added that Boeing’s optics system looked very good during the CDR.”⁹⁶

Figure F-1 shows part of an FEL facility at the Thomas Jefferson National Laboratory (Jefferson Lab) in Virginia. **Figure F-2** shows a simplified diagram of how an FEL works. **Figure F-3** shows a Jefferson Lab schematic of an FEL equipped with two “wigglers”—one for producing infrared (IR) laser light, and one for producing ultraviolet (UV) laser light. The FEL being developed by the Navy for shipboard use would likely produce only infrared light.

Figure F-1. Photograph of an FEL Facility



Source: Jefferson Lab news release of July 30, 2004, entitled “FEL Achieves 10 Kilowatts,” accessed November 16, 2010 at <http://www.jlab.org/news/releases/2004/0410kw.html>. The news release says that the release is “As released by the Office of Naval Research with images and captions from Jefferson Lab.” The caption to the photo in the news release states: “The Free-Electron Laser vault at Jefferson Lab showing the superconducting

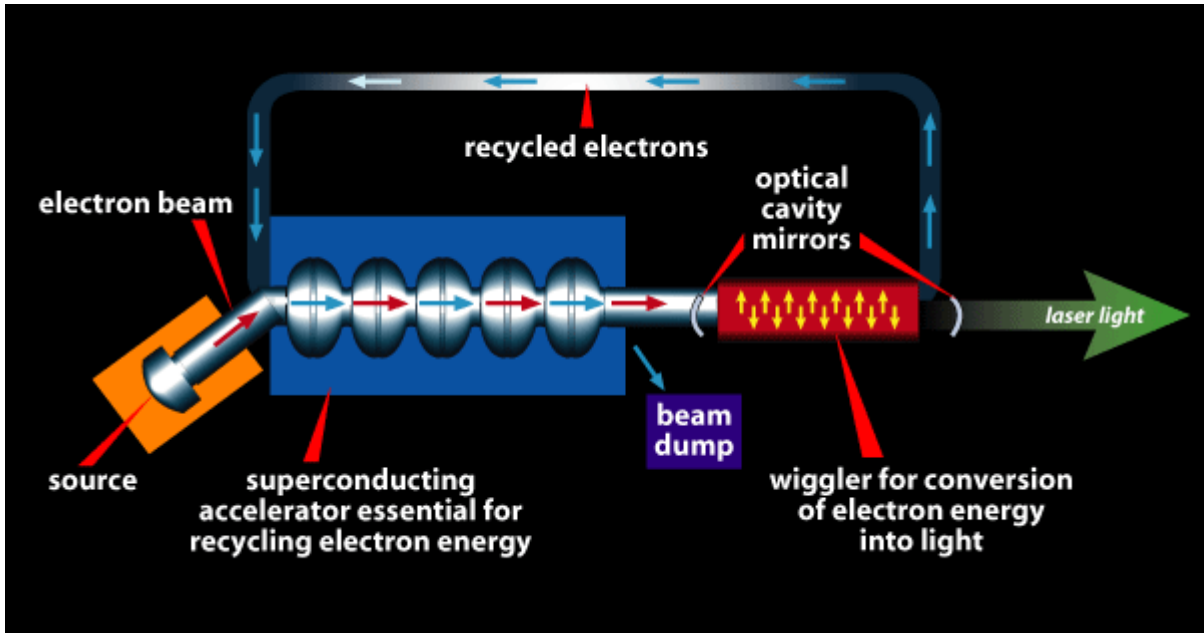
⁹⁴ Source: Navy information paper dated June 1, 2011, provided by the Navy to CRS and CBO on June 14, 2011.

⁹⁵ Mike McCarthy, “Navy’s Free Electron Laser Undergoing Design Review,” *Defense Daily*, March 21, 2012: 7.

⁹⁶ Megan Eckstein, “FEL Looks Good At CDR, But Project Halted In Favor of SSL Development,” *Inside the Navy*, March 26, 2012.

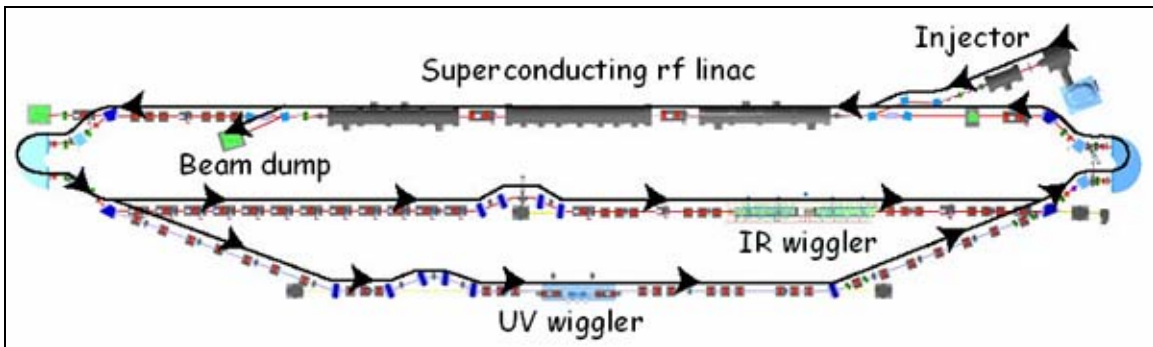
accelerator in the background and the magnetic wiggler in the foreground. The wiggler converts the electron beam power into laser light. Photo by Greg Adams, JLab.”

Figure F-2. Simplified Diagram of How an FEL Works



Source: Jefferson Lab web page providing an introduction to FELs, accessed November 16, 2010, at <http://www.jlab.org/FEL/feldescrip.html>.

Figure F-3. Schematic of an FEL
(Version with two “wigglers”)



Source: Jefferson Lab web page describing its FEL, accessed November 16, 2010 at <http://www.jlab.org/FEL/felspecs.html>. This FEL has two “wigglers”—one for producing infrared (IR) laser light, and one for producing ultraviolet (UV) laser light. The FEL being developed by the Navy for shipboard use would likely produce only infrared light. The arrows show the flow of electrons in the device, starting with the electron gun and injector in the upper-right corner. “Rf linac” means radio frequency linear accelerator.

Appendix G. Innovative Naval Prototypes (INPs)

The Office of Naval Research (ONR) is developing the 100 kW FEL as an Innovative Naval Prototype (INP). ONR describes INPs as follows:

[ONR's work on] Leap Ahead Innovations include Innovative Naval Prototypes (INPs) and Swampworks, and are technology investments that are potentially "game changing" or "disruptive" in nature. INPs achieve a level of technology suitable for transition in four to eight years. Innovative Naval Prototypes explore high 6.2 and 6.3 [research and development budget category] technologies that can dramatically change the way Naval forces fight. Programs in this category may be disruptive technologies that, for reasons of high risk or radical departure from established requirements and concepts of operation, are unlikely to survive without top leadership endorsement, and, unlike Future Naval Capabilities [another category of ONR's work], are initially too high risk for a firm transition commitment from the acquisition community. INPs should be identified based on a balanced combination of naval need and technology exploitation. Investments should be planned with the critical mass needed to achieve a level of technology maturity suitable for transition in four to eight years. Program Managers (PMs) are primarily selected from ONR, and in order to help facilitate the transition to the acquisition community, Deputy PMs are typically chosen from the Acquisition community. The CNR [Chief of Naval Research], in consultation with senior Navy and Marine Corps leadership, identifies candidate INPs that are then forwarded to Naval S&T [Science and Technology] Corporate Board (ASN-RDA, VCNO and the APMC) [the Assistant Secretary of the Navy, Research, Development, and Acquisition, the Vice Chief of Naval Operations, and the Assistant Commandant of the Marine Corps] for approval / disapproval. Free Electron Laser is an innovative naval prototype. Swampworks efforts are smaller in scope than INPs and are intended to produce results in one to three years. This category is where we typically accept higher risk in an effort to produce higher payoff for the warfighters.⁹⁷

⁹⁷ Source: Navy information paper on directed energy dated August 26, 2010.

Appendix H. DOD Technology Readiness Levels (TRLs)

DOD uses TRLs to characterize the developmental status of many weapon technologies. DOD defines its TRLs as follows:

- TRL 1: Basic principles observed and reported.
- TRL 2: Technology concept and/or application formulated.
- TRL 3: Analytical and experimental critical function and/or characteristic proof of concept.
- TRL 4: Component and/or breadboard validation in a laboratory environment.
- TRL 5: Component and/or breadboard validation in a relevant environment.
- TRL 6: System/subsystem model or prototype demonstration in a relevant environment.
- TRL 7: System prototype demonstration in an operational environment.
- TRL 8: Actual system completed and qualified through test and demonstration.
- TRL 9: Actual system proven through successful mission operations.⁹⁸

⁹⁸ Source: Department of Defense, *Technology Readiness Assessment (TRA) Deskbook*, July 2009, accessed online at http://www.dod.mil/ddre/doc/DoD_TRA_July_2009_Read_Version.pdf.

Appendix I. Protocol on Blinding Lasers

This appendix provides information on the international protocol on blinding lasers and its relationship to DOD laser programs, including the lasers discussed in this report.

Overview

The United States in 1995 ratified the 1980 Convention on Prohibitions or Restriction on the Use of Certain Conventional Weapons Which May be Deemed to be Excessively Injurious or to Have Indiscriminate Effects. An international review of the convention began in 1994 and concluded in May 1996 with the adoption of, among other things, a new Protocol IV on blinding laser weapons. The protocol prohibits the employment of lasers that are specifically designed to cause permanent blindness to the naked eye or to the eye with corrective eyesight devices.

The United States ratified Protocol IV on December 23, 2008, and it entered into force for the United States on July 21, 2009.⁹⁹ DOD views the protocol as fully consistent with DOD policy. DOD believes the lasers discussed in this report are consistent with DOD policy of prohibiting the use of lasers specifically designed to cause permanent blindness to the naked eye or to the eye with corrective eyesight devices.

Article-by-Article Discussion

Article 1 of the protocol prohibits the employment of “laser weapons specifically designed, as their sole combat function or as one of their combat functions, to cause permanent blindness to unenhanced vision, that is to the naked eye or to the eye with corrective eyesight devices.” DOD states that:

This prohibition is fully consistent with the policy of the Department of Defense, which is to prohibit the use of weapons so designed. Although the prospect of mass blinding was an impetus for the adoption of the Protocol, it was not the intent of the Conference to prohibit only mass blinding. Accordingly, under both the Blinding Laser Protocol and Department of Defense policy, laser weapons designed specifically to cause such permanent blindness may not be used against an individual enemy combatant.¹⁰⁰

⁹⁹ Treaties and Other International Acts Series 09-721.2, *Weapons, Blinding Laser Weapons (Protocol IV), Protocol Between the United States of America and Other Governments to the 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 of October 10, 1980*, accessed March 27, 2013, at <http://www.state.gov/documents/organization/190580.pdf>. See also United States Department of State, *Treaties in Force, A List of Treaties and Other International Agreements of the United States in Force on January 1, 2012*, page 483.

¹⁰⁰ Department of Defense, *CCW: Article by Article Analysis of the Protocol on Blinding Laser Weapons*, accessed online at http://www.acq.osd.mil/tc/treaties/ccwapl/artbyart_pro4.htm. In January 1997, Secretary of Defense William Perry issued a memorandum regarding DOD policy on blinding lasers which states in its entirety:

The Department of Defense prohibits the use of lasers specifically designed to cause permanent blindness and supports negotiations to prohibit the use of such weapons. However, 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
(continued...)

Article 2 of the protocol obligates parties to “take all feasible precautions to avoid the incidence of permanent blindness to unenhanced vision.” DOD states that “This requirement is also fully consistent with the policy of the Department of Defense which is to reduce, through training and doctrine, inadvertent injuries from the use of lasers designed for other purposes, such as range-finding, target discrimination, and communications.”¹⁰¹

Article 3 of the protocol states that “blinding as an incidental or collateral effect of the legitimate military employment of laser systems, including laser systems used against optical equipment, is not covered” by the Protocol. DOD states that this article “reflects a recognition of the inevitability of eye injury as the result of lawful battlefield laser use. Its use is an important measure in avoiding war crimes allegations where injury occurs from legitimate laser uses.”¹⁰²

DOD further states that

As a matter of policy, the United States will refrain from the use of laser weapons prohibited by the Protocol. Therefore, while the Blinding Laser Weapons Protocol does not legally apply to all armed conflicts, it is U.S. policy to apply the Protocol to all such conflicts, however they may be characterized, and in peacetime.... The Protocol is fully consistent with U.S. military interests, Department of Defense policy and humanitarian concerns generally. Accordingly, the United States should ratify it at an early date.¹⁰³

Excerpt from 2007 DSB Task Force Report

A 2007 report by a Defense Science Board (DSB) task force on directed energy weapons stated:

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 [i.e., due to] 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.

(...continued)

systems to be increasingly discriminate, thereby reducing collateral damage to civilian lives and property. The Department of Defense recognizes that accidental or incidental eye injuries may occur on the battlefield as the result of the use of lasers not specifically designed to cause permanent blindness. Therefore, we continue to strive, through training and doctrine, to minimize these injuries.

(Memorandum dated January 17, 1997, from Secretary of Defense William J. Perry to the secretaries of the military departments, et al, on DOD policy on blinding lasers, provided to CRS on October 4, 2010, by the Navy Office of Legislative Affairs.)

Paragraph 4.3 of DOD Instruction 3100.11 of March 31, 2000, on the illumination of objects in space by lasers, states: “The use of lasers specifically designed to cause permanent blindness in humans is prohibited, in accordance with [the above-cited January 17, 1997, memorandum from the Secretary of Defense].”

¹⁰¹ Department of Defense, *CCW: Article by Article Analysis of the Protocol on Blinding Laser Weapons*, accessed online at http://www.acq.osd.mil/tc/treaties/ccwapl/artbyart_pro4.htm.

¹⁰² Department of Defense, *CCW: Article by Article Analysis of the Protocol on Blinding Laser Weapons*, accessed online at http://www.acq.osd.mil/tc/treaties/ccwapl/artbyart_pro4.htm.

¹⁰³ Department of Defense, *CCW: Article by Article Analysis of the Protocol on Blinding Laser Weapons*, accessed online at http://www.acq.osd.mil/tc/treaties/ccwapl/artbyart_pro4.htm.

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, [as well as] the [international] 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. 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.¹⁰⁴ 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.¹⁰⁵

¹⁰⁴ The text of the 1997 Secretary of Defense memorandum quoted in footnote 100 is slightly different at this point. Instead of "legitimate laser systems," the 1997 memorandum uses the phrase "lasers not specifically designed to cause permanent blindness."

¹⁰⁵ [Report of] Defense Science Board Task Force on Directed Energy Weapons, Washington, December 2007, pp. xii-xiii. Ellipsis and material in brackets as in original.

Appendix J. Illumination of Objects in Space

In briefings on potential shipboard lasers, Navy officials noted DOD Instruction (DODI) 3100.11 of March 31, 2000, which states in part:

All DoD laser activities shall be conducted in a safe and responsible manner that protects space systems, their mission effectiveness, and humans in space, consistent with national security requirements, in accordance with [DoD Directive 3100.10, "Space Policy," July 9, 1999]. All such activities shall be coordinated with the Commander in Chief of U.S. Space Command (CINCSPACE) for predictive avoidance or deconfliction with U.S., friendly, and other space operations.¹⁰⁶

The technical community in the Navy believes that this instruction effectively requires the military services to implement measures for ensuring that objects in space face low or no exposure to laser energy. The technical community believes that this in turn would require that shipboard lasers incorporate so-called predictive avoidance (PA) software and/or other features that would prevent them from firing in the direction of an object in space. The community believes that two policy changes would be required to permit Navy surface ships to use shipboard lasers with power levels high enough that they could cause unwanted collateral damage to satellites:

- The community believes that current safety criteria relating to satellites are overly restrictive and should be replaced with a new policy that includes what the Navy views as more realistic safety criteria.
- The community believes that certain data relating to sensitive satellites should be removed from the PA system so that the classification level of the PA system can be lowered.

¹⁰⁶ Department of Defense Instruction Number 3100.11, March 31, 2000, on Illumination of Objects in Space by lasers, paragraph 4.2.

Appendix K. Section 220 of FY2000 Defense Authorization Act (P.L. 106-398)

As mentioned earlier (see footnote 79 in “Options for Congress”), the option of directing the Navy to develop and install lasers with certain capabilities on a certain number of Navy surface ships by a certain date could take the form of a provision broadly similar to Section 220 of the FY2001 defense authorization act (H.R. 4205/P.L. 106-398 of October 30, 2000), which set goals for the deployment of unmanned combat aircraft and unmanned combat vehicles. The text of Section 220 is as follows:

SEC. 220. UNMANNED ADVANCED CAPABILITY COMBAT AIRCRAFT AND GROUND COMBAT VEHICLES.

(a) GOAL- It shall be a goal of the Armed Forces to achieve the fielding of unmanned, remotely controlled technology such that—

(1) by 2010, one-third of the aircraft in the operational deep strike force aircraft fleet are unmanned; and

(2) by 2015, one-third of the operational ground combat vehicles are unmanned.

(b) REPORT ON UNMANNED ADVANCED CAPABILITY COMBAT AIRCRAFT AND GROUND COMBAT VEHICLES- (1) Not later than January 31, 2001, the Secretary of Defense shall submit to the congressional defense committees a report on the programs to demonstrate unmanned advanced capability combat aircraft and ground combat vehicles undertaken jointly between the Director of the Defense Advanced Research Projects Agency and any of the following:

(A) The Secretary of the Army.

(B) The Secretary of the Navy.

(C) The Secretary of the Air Force.

(2) The report shall include, for each program referred to in paragraph (1), the following:

(A) A schedule for the demonstration to be carried out under that program.

(B) An identification of the funding required for fiscal year 2002 and for the future-years defense program to carry out that program and for the demonstration to be carried out under that program.

(C) In the case of the program relating to the Army, the plan for modification of the existing memorandum of agreement with the Defense Advanced Research Projects Agency for demonstration and development of the Future Combat System to reflect an increase in unmanned, remotely controlled enabling technologies.

(3) The report shall also include, for each Secretary referred to in paragraphs (1)(A), (1)(B), and (1)(C), a description and assessment of the acquisition strategy for unmanned advanced capability combat aircraft and ground combat vehicles planned by that Secretary, which shall include a detailed estimate of all research and development, procurement, operation, support, ownership, and other costs required to carry out such strategy through the year 2030, and—

(A) in the case of the acquisition strategy relating to the Army, the transition from the planned acquisition strategy for the Future Combat System to an acquisition strategy capable of meeting the goal specified in subsection (a)(2);

(B) in the case of the acquisition strategy relating to the Navy—

(i) the plan to implement a program that examines the ongoing Air Force unmanned combat air vehicle program and identifies an approach to develop a Navy unmanned combat air vehicle program that has the goal of developing an aircraft that is suitable for aircraft carrier use and has maximum commonality with the aircraft under the Air Force program; and

(ii) an analysis of alternatives between the operational deep strike force aircraft fleet and that fleet together with an additional 10 to 20 unmanned advanced capability combat aircraft that are suitable for aircraft carrier use and capable of penetrating fully operational enemy air defense systems; and

(C) in the case of the acquisition strategy relating to the Air Force—

(i) the schedule for evaluation of demonstration results for the ongoing unmanned combat air vehicle program and the earliest possible transition of that program into engineering and manufacturing development and procurement; and

(ii) an analysis of alternatives between the currently planned deep strike force aircraft fleet and the operational deep strike force aircraft fleet that could be acquired by fiscal year 2010 to meet the goal specified in subsection (a)(1).

(c) FUNDS- Of the amount authorized to be appropriated for Defense-wide activities under section 201(4) for the Defense Advanced Research Projects Agency, \$100,000,000 shall be available only to carry out the programs referred to in subsection (b)(1).

(d) DEFINITIONS- For purposes of this section:

(1) An aircraft or ground combat vehicle has ‘unmanned advanced capability’ if it is an autonomous, semi-autonomous, or remotely controlled system that can be deployed, re-tasked, recovered, and re-deployed.

(2) The term ‘currently planned deep strike force aircraft fleet’ means the early entry, deep strike aircraft fleet (composed of F-117 stealth aircraft and B-2 stealth aircraft) that is currently planned for fiscal year 2010.

(3) The term ‘operational deep strike force aircraft fleet’ means the currently planned deep strike force aircraft fleet, together with at least 30 unmanned advanced capability combat aircraft that are capable of penetrating fully operational enemy air defense systems.

(4) The term ‘operational ground combat vehicles’ means ground combat vehicles acquired through the Future Combat System acquisition program of the Army to equip the future objective force, as outlined in the vision statement of the Chief of Staff of the Army.

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