Center for Strategic and Budgetary Assessments

CHANGING THE GAME

THE PROMISE OF DIRECTED-ENERGY WEAPONS

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With Chris Dougherty

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EXECUTIVE SUMMARY

America's ability to project conventional power abroad is eroding swiftly as state and non-state actors acquire advanced capabilities to offset the U.S. military's strengths across all operating domains—air, land, sea, space, and cyberspace. Potential adversaries are pursuing guided weapons and other sophisticated systems that are designed to threaten the U.S. military's freedom of action and its overseas basis. Moreover, many of these threats, particularly precision-guided cruise and ballistic missiles, are on balance less expensive and easier to replace than the expensive kinetic weapons the U.S. military relies on to defend against them. As a result, America's future power projection operations may be far more challenging and inordinately more costly compared to conventional operations that it has undertaken over the last twenty years.

To change this emerging dynamic, the Department of Defense should invest in new technologies that will help the U.S. military retain its freedom of action and create cost-exchange ratios that favor the United States. Throughout history, technological breakthroughs such as machine guns, armored vehicles, submarines, precision-guided weapons, and stealth aircraft have proven to be great sources of operational advantage for militaries that were willing and able to exploit them. This report addresses the potential of a new family of emerging technologies known as directed energy (DE) to achieve similar results.[1]

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1 Directed energy is used by DoD to describe a wide range of non-kinetic capabilities that produce "a beam of concentrated electromagnetic energy or atomic or subatomic particles" to "damage or destroy enemy equipment, facilities, and personnel" in the air, sea, space and land domains. DE devices are defined as systems "using directed energy primarily for a purpose other than as a weapon" that may include laser rangefinders and designators used against sensors that are sensitive to light. Finally, DE warfare includes "actions taken to protect friendly equipment, facilities, and personnel and retain friendly use of the electromagnetic spectrum." See Joint Publication 1-02, "Department of Defense Dictionary of Military and Associated Terms," November 8, 2010, pp. 99-100, available at http://www.dtic.mil/doctrine/new_pubs/jp1_02.pdf.

Thus, this report has two principal objectives. The first is to examine DE as one particularly promising source of operational advantage for the U.S. military. The unique attributes of future DE capabilities—the ability to create precise, tailorable effects against multiple targets near-instantaneously and at a very low cost per shot—have great potential to help the Department of Defense (DoD) break from a program of record that continues to procure increasingly expensive military technologies with diminishing operational returns. For example, in future conflicts with capable enemies possessing large inventories of guided missiles, it may be operationally risky and cost-prohibitive for the U.S. military to continue to rely exclusively on a limited number of kinetic missile interceptors. Such a "missile competition" could allow an adversary to impose costs on U.S. forces by compelling them to intercept each incoming missile with far more expensive kinetic munitions.

There may be less resource-intensive options that could help the United States to maintain an advantage in such conflicts. Offensive and defensive DE capabilities, including high-energy lasers and high-power microwave weapons, could provide U.S. forces with nearly unlimited magazines to counter incoming missiles at a negligible cost per shot. When integrated with kinetic capabilities to support new operational concepts such as AirSea Battle,[2] these DE weapons could help reverse the cost-imposition calculus of future missile competitions in favor of the United States. U.S. forces could also use DE capabilities to gain a significant advantage over opponents capable of launching swarms of fast attack craft; armed unmanned aircraft; and guided rockets, artillery, mortars, and missiles (G-RAMM). Moreover, DE systems could help counter these threats with significantly less collateral damage than that caused by kinetic defenses, an attribute that would be especially important during future operations in urban terrain.

The report's second objective is to assess emerging DE technologies that have the potential to transition to real-world military capabilities over the next twenty years.

In the mid term (the next five to ten years), it may be possible to use mature laser technologies to create deployable, ground-based weapons to defend forward bases against aircraft, G-RAMM, and ballistic missiles. Because of their potential to overcome the size, weight, and magazine depth challenges posed by current technology chemical lasers, new electrically powered, solid-state lasers (SSLs) may be the most promising alternatives for laser weapons that can be mounted on large mobile platforms such as surface naval vessels. Given sufficient

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[2] For additional information on AirSea Battle, see Jan van Tol with Mark Gunzinger, Andrew Krepinevich, and Jim Thomas, *AirSea Battle: A Point-of-Departure Operational Concept* (Washington, DC: Center For Strategic and Budgetary Assessments, 2010). Also see Mark Gunzinger with Chris Dougherty, *Outside-In: Operating from Range to Defeat Iran's Anti-Access and Area-Denial Threats* (Washington, DC: Center For Strategic And Budgetary Assessments, 2011).

resources, it may also be feasible in the mid term to develop high-power microwave (HPM) emitters carried by aircraft or cruise missiles that could degrade, damage, or destroy the electronic hardware that enables enemy anti-access/area-denial (A2/AD) threats.

In the long term (the next ten to twenty years), it is expected that technological advances will continue to reduce the volume, weight, and cooling requirements of high-power SSLs, creating opportunities to integrate them into small aircraft and tactical ground vehicles. By the late 2020s, it may also be possible to develop ship-based free electron lasers (FELs) with power outputs sufficient to interdict more hardened targets, including ballistic-missile reentry vehicles.

Although DoD is pursuing science and technology (S&T) initiatives related to these concepts, it is likely that many, if not most of them, will remain at the conceptual level or will be terminated after their initial demonstrations. The lack of institutional support for DE concepts has a number of causes. Previous high-profile DE programs failed to deliver on promises of game-changing capabilities. These failures have increased the U.S. military's reluctance to adopt a new generation of DE weapons concepts that are based on significantly more mature technology. Other barriers include institutional desires for "perfect" technological solutions and insufficient DE program funding. The latter problem may not soon improve, considering downward pressures on the defense budget.

This report suggests that cultural factors and the lack of resources, not technology maturity, are now the most significant barriers to developing major new DE capabilities over the next decade. While developing and fielding these capabilities will require up-front investments, they have the potential to reduce DoD's dependence on costly kinetic weapons that require extensive logistics networks to replenish, yielding savings that could be used for other priorities. DE capabilities should therefore be a key part of developing a future capability portfolio aligned with DoD's objectives of creating "a smaller, lighter, more agile, flexible joint force that has to conduct a full range of military activities" while ensuring that U.S. forces "always maintain a technological edge" over its future enemies.[3]

To help overcome barriers to developing new DE weapons, it may be useful to acknowledge that directed-energy capabilities alone will be insufficient to counter the challenges posed by enemies possessing advanced precision-guided weapons. Rather, DE technologies can lead to new applications that could, *in combination with kinetic capabilities,* enable new operational concepts that are designed to counter emerging A2/AD networks. In other words, DE capabilities are not an existential threat to the U.S. military's kinetic weapons programs and, in fact, would complement and increase the effectiveness of these systems to

[3] See Thom Shanker and Elisabeth Bumiller, "Weighing Pentagon Cuts, Panetta Faces Deep Pressures," *New York Times*, November 6, 2011, available at http://www.nytimes.com/2011/11/07/world/panetta-weighs-military-cuts-once-thought-out-of-bounds.html.

create more robust layered defenses. Ultimately, however, it could take a significant "win"—the successful transition of a major new high-power DE weapon system to operational status—to prove the value of this technology to Service leaders and Combatant Commanders. DE weapons, like many innovative military technologies that preceded them, may have to be proven in combat before DoD grasps their full potential.

This report concludes by recommending five initiatives that could be part of an acquisition plan that focuses DoD investments on the most promising DE initiatives. It also recommends that such a plan should consider the maturity of DE technologies and their supporting requirements, including space, power, and cooling needs, that would affect their integration with operational military platforms.

> DoD should support the U.S. Navy as the "first adopter" for weaponizing an SSL capable of producing 100 kilowatts or more of output energy. Surface ships with sufficient power, volume, and cooling capacity are particularly well-suited as platforms for SSLs that could become part of a layered defense against unmanned aerial vehicles (UAVs), anti-ship cruise missiles (ASCMs), and fast attack craft.

> The U.S. Army and Air Force should leverage mature laser technologies to develop deployable, ground-based DE defenses against air and missile threats to bases in the Western Pacific and Southwest Asia. Combined with kinetic defenses, a network of DE weapons could shift the cost-imposition calculus in favor of U.S. power-projection forces. The U.S. Marine Corps should leverage Navy and Army high-energy laser and SSL development programs to accelerate fielding of a Ground-Based Air Defense System.

> The U.S. Air Force and U.S. Navy should lead DoD's efforts to develop new HPM weapons that could be integrated into manned and unmanned aircraft, cruise missiles, and ground vehicles. Unlike state-of-the-art SSLs, HPM weapons appear to be sufficiently mature and compact to be weaponized in the near term into packages that could be carried by air platforms. The Air Force and Navy should continue to pursue technologies that could increase HPM power outputs and ranges, as well as concepts that could lead to recoverable and reusable HPM systems capable of attacking scores of targets per sortie.

- The military Services should work with the Commandant of the U.S. Marine Corps, DoD's executive agent for non-lethal weapons, to transition advanced, non-lethal DE concepts being developed by the Joint Non-Lethal Weapons Directorate to programs of record. A more concerted, defense-wide effort is needed to improve Combatant Commanders' understanding of the potential for non-lethal DE capabilities to support a wide range of operations.
- Additional lethality testing to determine the effects of SSL and HPM systems against various classes of air and ground threats in operationally relevant environments could inform future DE requirements and investment decisions. Testing in the near term should seek to develop better data on DE lethality against vehicles, small boats, UAVs, cruise and ballistic missiles, as well as the impact of aerosols, humidity, and obscurants on laser weapons operating in maritime and ground battlefield environments.

INTRODUCTION

> When a new technology appears in business or war, advantages in cost or efficiency—albeit initially marginal—may be clear almost from its appearance. Conversely, decades or even centuries may pass before we conclude that the new technology is not a substitute for the old but offers the opportunity to move into a new dimension previously not available or even conceived. Such myopia often leads otherwise competent observers to underestimate significantly the new technology's potential.
>
> —Colonel John A. Warden III[4]

Today, the United States retains an unparalleled ability to project conventional military power abroad. This ability is eroding swiftly, however, as state and non-state actors pursue asymmetric approaches to offset America's military strengths in the air, on land, at sea, and in space and cyberspace. The continuing proliferation of advanced military technologies, such as ASCMs, ballistic missiles, and integrated air defense systems (IADS), are underpinning the development of battle networks that guard the approaches to the Western Pacific, Persian Gulf, and other regions of vital interest to the United States. Moreover, many of these A2/AD threats, particularly precision-guided cruise and ballistic missiles, are on balance less expensive and easier to replace than the kinetic systems the U.S. military uses to defend against them.[5] This could allow an enemy to impose costs on U.S. forces.

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4 Colonel John A. Warden III, "Strategy and Airpower," *Air & Space Power Journal*, 25, No. 1, Spring 2011, p. 64, available at http://www.airpower.au.af.mil/airchronicles/apj/2011/2011-1/2011_1_04_warden.pdf. Colonel Warden was a commandant of the U.S. Air Force's Air Command and Staff College and is acknowledged as one of the architects of the 1991 Operation Desert Storm air campaign.

5 See van Tol et al., *AirSea Battle*; and Gunzinger, *Outside-In*.

In lieu of simply "buying more of the same" in response to these challenges, DoD should invest in new military technologies that can shift this unfavorable cost-exchange ratio in favor of the United States. The imperative to pursue such a course is particularly strong in an age of declining defense budgets such as the one in which the United States finds itself today. This report focuses on future offensive and defensive DE capabilities that have the potential to create new operational advantages for the U.S. military. Combined with kinetic weapons, future DE weapon systems could help the United States buy back its ability to project military power at acceptable levels of risk and cost.

As with any major evolution in military technologies, there are barriers that must be overcome before significant new DE capabilities can be fielded. Technological challenges include the need to reduce the volume, weight, power, and cooling requirements of high-energy SSLs to levels that allow them to be integrated into aircraft and ground vehicles. DoD must also overcome institutional obstacles that hinder the transition of DE technologies to full-scale programs of record. Leaders in the Office of the Secretary of Defense, Service Departments, and Combatant Commands need to recognize the potential of emerging DE technologies and champion their development through DoD's myriad requirements, acquisition, and budgeting processes.

APPROACH

This assessment has two primary objectives: (1) to examine the potential of new DE capabilities to enable a breakout from an emerging operational stalemate and shift cost-exchange ratios in favor of the U.S. military; and (2) to identify DE technologies that have the greatest promise to transition into the Pentagon's program of record over the next ten to twenty years.

Toward this end, Chapter One begins by summarizing the characteristics of a mature precision-guided weapons regime and its potential impact on future U.S. operations. Chapter Two continues by assessing the unique attributes of high-energy DE systems that could confer significant advantages on U.S. forces and help DoD move toward a favorable cost-benefit ratio against adversaries with capable A2/AD battle networks. Chapter Three evaluates a variety of promising DE concepts that could be transitioned to full-scale weapons programs. Chapter Four postulates how a number of these DE applications could be used to support future operations against A2/AD battle networks emerging in the Western Pacific and Persian Gulf. Chapter Five summarizes key technological, institutional, and resource challenges that must be overcome if the U.S. military is to field these new, potentially game-changing DE capabilities. The paper concludes by recommending elements of a weapons development program that focuses on transitioning the most promising DE technologies to operational systems.

CHAPTER 1 > **TOWARD AN OPERATIONAL STALEMATE?**

A distinctive "American way of war" has evolved over the last sixty years, first to meet the Soviet threat during the Cold War and then to project forces abroad to support regional contingency operations. A number of attributes have come to characterize this way of war. Military assets that underpin major U.S. operations typically consist of large, high-signature formations such as carrier strike groups (CSGs), squadrons of aircraft, and brigade combat teams. Deploying and sustaining these formations in distant theaters has led to the development of sophisticated logistics networks. Once deployed, U.S. forces rely on large theater bases that act as secure staging areas for combat and combat support operations. Tying all of these elements together is an extensive information infrastructure that gathers and shares intelligence, provides accurate navigation and targeting data, and coordinates complex operations over extended distances.

In the past, this way of war has been described as massing destructive combat power to wage campaigns of attrition against an enemy's military forces.[6] With the advent of advanced guided weapons, the Industrial Age concept of massing fires to conduct wars of attrition has largely been supplanted by the ability to create precise effects on specific targets. Since the end of the Cold War, the U.S. military has assumed that its sophisticated reconnaissance-strike complex (RSC), composed of advanced sensors, precision-guided weapons, and information networks, would not be matched by regional military powers.[7] This assumption appeared to have been validated during operations in which U.S. forces dominated

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6 See Russell F. Weigley, *The American Way of War* (Bloomington, IN: Indiana University Press, 1973).

7 For a description of a "reconnaissance-strike complex," see Barry D. Watts, *The Maturing Revolution in Military Affairs* (Washington, DC: Center for Strategic and Budgetary Assessments, 2011), pp. 1-3.

the skies over Kosovo, twice made short work of Saddam Hussein's military, and quickly knocked the Taliban out of power in Afghanistan.[8]

These successes did not occur in a closed system, however. Potential adversaries have observed the effectiveness of America's RSC and are developing capabilities to counter it in all operating domains. Thus, it is important to understand how potential opponents are adapting and why these adaptations are invalidating America's traditional power-projection assumptions.[9] Accordingly, the following sections briefly summarize the general characteristics of a maturing precision-guided weapons regime and its potential impact on future U.S. power-projection operations.

CHINA'S A2/AD RECONNAISSANCE-STRIKE COMPLEX

Although projecting military force overseas has always been a challenging and costly endeavor for the United States, the proliferation of competing RSCs is likely to make future U.S. operations far more difficult. The People's Republic of China (PRC), for example, is developing a sophisticated RSC to guard its eastern air and maritime approaches. This RSC, which is actually a network of networks, includes a variety of counter-air, counter-space, and counter-network capabilities as well as extended-range precision strike weapons and surveillance systems to support over-the-horizon attacks against targets at sea and on land.

China has designed its RSC to target key dependencies underpinning U.S. military operations. After watching the fate that befell Saddam Hussein, who allowed the United States and its coalition partners to mass a decisive force along Iraq's borders in 1991 and 2003, China designed an A2/AD strategy to exploit the U.S. military's dependence on a small number of main operating bases located in the Western Pacific.[10] As part of this strategy, China apparently plans to target these bases as well as the extended air and sea lines of communication that are essential to sustaining U.S. power-projection operations. China also appears to be preparing to supplement these actions by launching kinetic and non-kinetic attacks against surveillance and long-haul communications battle networks to

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[8] Ibid., pp. 7-8.

[9] As Barry Watts has observed, it is important to assess the U.S. military's RSC "relation to capable adversaries with their own precision-strike capabilities rather than relative to opponents with third-rate military capabilities." Ibid., p. 8.

[10] Anti-access capabilities/strategies are used to prevent or constrain the deployment of opposing forces into a theater of operations, whereas area-denial capabilities/strategies are used to restrict their freedom of maneuver once in theater. For an overview of A2/AD challenges, see Andrew F. Krepinevich, *Why AirSea Battle?* (Washington, DC: Center for Strategic and Budgetary Assessments, 2010).

render deployed U.S. forces nearly deaf, mute, and blind.[11] Against such challenges, it is not clear that the U.S. military could execute its traditional post-Cold War concepts of operation effectively, or do so at acceptable levels of risk.[12]

IRAN'S EMERGING A2/AD STRATEGY

In many ways, China's military modernization is a harbinger of a broader trend in which smaller regional powers and even non-state actors are seeking to develop or procure similar asymmetric capabilities. Iran, for instance, is pursuing an A2/AD strategy that leverages the unique geography of the Persian Gulf region to its advantage. Iran has fielded ASCMs and fast attack craft armed with rockets that it can use in large numbers to "swarm" U.S. warships operating in the confined waters of the Strait of Hormuz. Iran's fleet of conventionally powered submarines, including several Russian-built *Kilo*-class boats and a larger number of "midget" submarines, could attack surface vessels directly or lay mines to channelize U.S. naval operations.[13]

Over the last two decades, Iran has also acquired a large inventory of road-mobile, short-range ballistic missiles and a small but growing number of longer-range missiles. While these missiles are not as accurate as their Chinese counterparts, Iran could use them to threaten, coerce, and punish its neighbors, much as it did during the "War of the Cities" with Iraq in the 1980s.[14] In other words, instead of using its ballistic missiles to attack U.S. forces in the field directly, Iran could employ them in a campaign intended to compel Persian Gulf states to deny overflight

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[11] On the PRC's military modernization and strategy, see Thomas J. Christensen, "Posing Problems Without Catching Up: China's Rise and Challenges for U.S. Security Policy," *International Security*, 25, No. 4, Spring 2001; Roger Cliff et al, *Entering the Dragon's Lair: Chinese Antiaccess Strategies and Their Implications for the United States* (Santa Monica, CA: RAND Corporation, 2007); and Randall Schriver and Mark Stokes, *Evolving Capabilities of the Chinese People's Liberation Army: Consequences of Coercive Aerospace Power for United States Conventional Deterrence* (Washington, DC: Project 2049 Institute, 2008).

[12] For a more complete overview of the assumptions underpinning U.S. military operational concepts for projecting power since the end of the Cold War, see van Tol et al, *AirSea Battle*, pp. 50-52; and Gunzinger, *Outside-In*, pp. 14-18.

[13] *Iran's Naval Forces: From Guerrilla Warfare to Modern Naval Strategy* (Washington, DC: Office of Naval Intelligence, 2009), pp. 13, 17-18; Steven R. Ward, "The Continuing Evolution of Iran's Military Doctrine," *Middle East Journal*, 59, No. 4, Autumn 2005, pp. 568-569; and David Eshel, "David and Goliath," *Aviation Week and Space Technology*, March 28, 2010.

[14] For a summary of Iran's missile capabilities, see National Air and Space Intelligence Center, *Ballistic and Cruise Missile Threat* (Wright-Patterson Air Force Base: National Air and Space Intelligence Center, 2009); Anthony Cordesman and Adam C. Seitz, *Iranian Weapons of Mass Destruction: The Birth of a Regional Nuclear Arms Race?* (Santa Barbara, CA: Praeger, 2009); Alan Cowell and Nazila Fathi, "Iran Test-Fires Missiles That Put Israel in Range," *New York Times*, September 28, 2009; and Michael Slackman, "Iran Says It Tested Upgraded Missile," *New York Times*, December 16, 2009.

access and bases to U.S. forces, thus undercutting the United States' ability to project power into the region.

NON-STATE ACTORS

The low cost of many guided weapons, combined with their potential to terrorize local populations, may make them a weapon of choice for non-state actors such as irregular terrorist groups. During the July 2006 conflict in southern Lebanon, Hezbollah fighters trained and equipped by Iran and Syria used large numbers of unguided weapons combined with a handful of guided munitions, such as anti-tank guided missiles (ATGMs) and a C-802 ASCM, against Israeli forces.[15] Hezbollah has since improved its strike capabilities by acquiring additional ASCMs and advanced man-portable air defense systems (MANPADS). Hezbollah may also possess solid-fueled M-600 surface-to-surface missiles, a version of Iran's Fateh-110 missile, which have a range of nearly 110 nautical miles (nm).[16]

Given this continuing "proliferation of precision" and the diffusion of other advanced military technologies to state and non-state actors, the day may be fast approaching when the U.S. military will no longer be able to operate from forward sanctuaries and use its superior RSC to overwhelm its opponents. Deep magazines of guided munitions and the ability to exploit internal lines of operation may confer significant advantages to forces opposing a U.S. military that remains dependent on a small number of theater bases, extended lines of communication, and capabilities that are increasingly expensive to develop, procure, maintain, and deploy.

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IMPLICATIONS FOR U.S. MILITARY OPERATIONS

One Example: The Missile Salvo Competition

This dynamic is perhaps best illustrated by the "competition" between a deployed U.S. force and a regional power that is equipped with a large magazine of precision-guided ballistic missiles. In the event of a conflict with China, for example, the People's Liberation Army (PLA) 2nd Artillery Corps could launch multiple

15 For a description of Hezbollah's strategy, tactics, and capabilities during the 2006 conflict, see Matt M. Matthews, *We Were Caught Unprepared: The 2006 Hezbollah-Israeli War* (Fort Leavenworth, KS: Combat Studies Institute Press, 2008); and Andrew Exum, *Hizballah at War: A Military Assessment* (Washington, DC: Washington Institute for Near East Policy, 2006).

16 Barak Ravid, "Israel to UN: Hezbollah Has Tripled its Land-to-Sea Missile Arsenal," *Haaretz*, October 31, 2007; Nicholas Blanford, "Hizballah Prepares for the Next War," *Time*, May 10, 2010; Charles Levinson and Jay Solomon, "Syria Gave Scuds to Hezbollah, U.S. Says," *Wall Street Journal*, April 14, 2010; and Alon Ben-David, "Israel Sees Increased Hezbollah Capability," *Aviation Week and Space Technology*, May 18, 2010.

ballistic missile salvo attacks to overwhelm the limited kinetic missile defenses of U.S. bases in Japan and Guam. These attacks may be far too large to counter effectively or affordably with kinetic interceptors or by other traditional measures, such as hardening base facilities.[17] Similarly, Iran is fielding a large number of short- and medium-range ballistic missiles that can reach target areas across the Middle East, some variants of which may be capable of carrying chemical, biological, or nuclear warheads.

Assuming DoD's program of record does not change, countering missile salvos launched by the PLA, Iran, or another regional power will depend on the effective use of kinetic defenses such as $3.3 million Patriot Advanced Capability-3 (PAC-3) missiles, $9 million Terminal High Altitude Area Defense (THAAD) missiles, and $10-15 million Standard Missile-3s (SM-3).[18] At these prices, defending against a salvo of thirty ballistic missiles could cost approximately $700 million, assuming two interceptors are launched at each incoming round in a "shoot-look-shoot" tactic designed to maximize the probability of a successful intercept.[19] This estimate excludes the cost of repairing damage inflicted by probable missile "leakers" that successfully elude intercepts.[20] Conversely, the enemy's price for such a salvo could be approximately 10 to 15 percent of the U.S. military's cost to defend against it.[21] Thus, while America's precision RSC has been a foundation for pro-

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[17] Department of Defense, Office of the Secretary of Defense, *Annual Report to Congress on the Military Power of the People's Republic of China* (Washington, DC: Department of Defense, 2010), pp. 1- 2, 27, 31.

[18] See "DoD News Briefing with Secretary Gates and Gen. Cartwright," September 17, 2009, accessible at http://www.defense.gov/transcripts/transcript.aspx?transcriptid=4479. During a news conference to explain DoD's Europe-based missile-defense system, General Cartwright stated that a PAC-3 costs about $3.3 million per missile; a SM-3 Block I, Mod A about $9.5–10 million; a SM-3 Block IB about $13–15 million; and a THAAD missile about $9 million. These estimates exclude the cost of the missiles' launch platforms and supporting infrastructure.

[19] Using multiple interceptors to achieve a high probability of kill against an incoming missile is a standard operating procedure. See Lieutenant General Patrick O'Reilly, "Unclassified statement before the House Appropriations Committee Defense Subcommittee," April 2, 2009, available at http://democrats.appropriations.house.gov/images/stories/pdf/def/Patrick_OReilly_04_02_09.pdf. The $700 million estimate is also based on the average cost of using a mix of PAC-3, THAAD, and SM-3s to counter the salvo.

[20] Costs would escalate dramatically should an aggressor choose to use ballistic missiles equipped with weapons of mass destruction (WMD). See Philip E. Coyle, former Assistant Secretary of Defense and Director, Operational Test and Evaluation, who reported in 2009 that PAC-3s had achieved twenty-one successful missile intercepts in twenty-nine attempts; the Aegis Combat System using Standard Missiles intercepted seventeen targets in twenty-one attempts; and THAAD had hit six targets in eight attempts since 2006. See Philip E. Coyle, briefing titled "Issues Facing U.S. Ballistic Missile Defense, Center for Defense Information," July 21, 2009, slides 30-33, available at http://www.armscontrol.org/system/files/Coyle_Missile_Defense_0.ppt.

[21] While the cost of domestically produced missiles such as China's Dong Feng and Iran's Shahab series are difficult to ascertain, estimates can be made from similar missiles. From 1987 through 2000, North Korea exported 300 to 400 Scud missile variants, of which Iran's Shahab series is a derivative. The estimated cost per missile ranged from $1–3 million. See Dinshaw Mistry, *Containing Missile Proliferation: Strategic Technology, Security Regimes, and International Cooperation in Arms Control* (Seattle: University of Washington, 2003), p. 130.

There are less resource-intensive, asymmetric approaches that could help shift the cost-exchange ratio in favor of U.S. forces.

jecting military power over the last two decades, the maturation of *competing* RSCs may lead to situations in which the high cost of defending forward bases and forces using conventional weapons could greatly hinder U.S. operations.

What are the alternatives for breaking out of this unfavorable dynamic and regaining the operational initiative? One approach would be to simply counter the problem symmetrically by acquiring additional kinetic defenses. This would, however, do nothing to alter the aforementioned unfavorable cost-exchange ratio. Another alternative might be to further harden and disperse U.S. military bases located in critical regions. While diversifying and increasing the resiliency of the U.S. military's forward posture is desirable, it could be costly and might require new host nation agreements in politically sensitive areas. Furthermore, enemies with adequate resources could offset such an approach by expanding their missile arsenals and developing penetrating warheads.

There are less resource-intensive, asymmetric approaches that could help shift the cost-exchange ratio in favor of U.S. forces. For example, the U.S. military could develop new operational concepts to regain its freedom of action at strategic distances. Anti-access strategies utilizing extended-range precision-strike capabilities depend on non-line-of-sight command, control, and targeting networks. This creates an opportunity for U.S. forces to conduct operations that "blind" an opposing battle network, thereby reducing the effectiveness of an enemy's long-range strikes against mobile targets. Although still able to attack known, fixed locations such as major airfields and ports, without an accurate picture of the extended battlespace an enemy could neither assess the effectiveness of its strikes nor confirm the presence of U.S. forces at targeted locations. This could induce an opposing force to waste its ballistic and cruise missiles by conducting unnecessary restrikes or expending ordnance against targets with negligible military value.

Another option would be to employ novel operational concepts enabled by new technologies. Fielding directed-energy weapons that could provide nearly unlimited magazines to counter enemy threats for a negligible cost per shot would enable new constructs such as AirSea Battle, as assessed in the next chapter. These weapons could improve the U.S. military's ability to defend bases and maneuver units that are within range of an enemy's strike systems. Moreover, they could enable land- and sea-based air forces to operate from staging locations that are closer to an enemy's homeland, which in turn could increase the number of offensive strikes that U.S. forces could conduct in a given period of time. The end result could be a breakout from an operational stalemate created by capable A2/AD weapons complexes as well as a reversal of the cost-exchange calculus in favor of the U.S. military.

SUMMARY

The emergence of competing RSCs may create an operating environment that "render(s) deploying large forces overseas and sustaining them through ports and fixed bases, too costly in terms of casualties and equipment attrition," thereby obviating the American way of war.[22] To break out of this cost-imposing paradigm and regain the initiative, DoD should adopt innovative operational concepts such as AirSea Battle and field new military technologies capable of countering an adversary's missile magazine in an affordable, asymmetric manner. Since other Center for Strategic and Budgetary Assessments (CSBA) reports have addressed the need for DoD to develop new operational concepts and long-range surveillance and strike capabilities, the remainder of this assessment will focus on DE technologies that have the potential to support these objectives.[23]

DoD should adopt innovative operational concepts such as AirSea Battle and field new military technologies capable of countering an adversary's missile magazine in an affordable, asymmetric manner.

[22] Watts, *The Likely Future Course of the Evolution in Military Affairs*, p. 30.

[23] See Mark Gunzinger, *Sustaining America's Strategic Advantage in Long-Range Strike* (Washington DC: Center for Strategic and Budgetary Assessments, September 2010); Gunzinger, Outside-In; and van Tol et al., AirSea Battle.

CHAPTER 2 > **A FAMILY OF TECHNOLOGIES COMING OF AGE**

Since the end of the Cold War, the U.S. military has become accustomed to deploying large, technologically superior forces abroad to overwhelm opposing militaries. Today, the United States is facing the possibility that the widespread proliferation of precision-guided weapons and other sophisticated technologies will significantly alter the character of future conflicts. Indeed, the United States may find itself in situations where deploying military forces could incur excessive risk. Given these circumstances, the United States should be wary of committing to a defense program that continues to prioritize military capabilities with flattening or declining cost-benefit ratios, as noted by Secretary of Defense Robert M. Gates:

> When it comes to procurement, for the better part of five decades, the trend has gone toward lower numbers [of systems] as technology gains have made each system more capable. In recent years, these platforms have grown ever more baroque, have become ever more costly, are taking longer to build, and are being fielded in ever-dwindling quantities. Given that resources are not unlimited, the dynamic of exchanging numbers for capability is perhaps reaching a point of diminishing returns.[24]

[24] Robert M. Gates, "A Balanced Strategy: Reprogramming the Pentagon for a New Age," *Foreign Affairs*, January 2009, p. 5, available at http://www.foreignaffairs.com/articles/63717/robert-m-gates/a-balanced-strategy. This state of affairs is similar to that faced by battleships early in World War II: "the Japanese attack on Pearl Harbor in December 1941 ushered in a new era of naval warfare. Never itself at risk from heavy guns or of being out maneuvered, the attacking force inflicted more damage than could reasonably have been expected from even the most successful conventional engagement. War is not about chivalry and morals so much as profit and loss, and the Japanese loss of 29 aircraft brought a huge (material) dividend. The big gun still enjoyed immense prestige but had reached that stage of development where vast inputs of research and experiment yielded ever-smaller improvements. At this point in any technology, a step change is required." Bernard Ireland, *Jane's Battleships of the 20th Century* (New York: Harper Collins, 1996), p. 180.

To reverse this unfavorable trend, DoD should place greater emphasis on new technologies that would help regain the U.S. military's freedom of action in future, non-permissive operating environments. History is replete with examples of technological innovations that have permitted militaries to shift from one warfare regime to another. The advent of steam-powered ironclad vessels, the invention of the machine gun, and the development of motorized armored vehicles are all well-known examples of technologies that enabled major advances in military effectiveness once they were incorporated into new forms of military operations. More recently, the maturation of stealth aircraft and precision-guided weaponry have given U.S. air forces advantages that have served them well over the last twenty years.

As guided munitions such as ASCMs, anti-ship ballistic missiles (ASBMs), and G-RAMM proliferate, defensive approaches that rely solely on expensive, one-time-use interceptors are becoming operationally unfeasible and fiscally unsustainable.

Today, emerging A2/AD battle networks pose new operational challenges for the U.S. military, challenges for which present solutions, which are based on incrementally improving current technologies, may be both inadequate and too expensive. Simply put, as guided munitions such as ASCMs, anti-ship ballistic missiles (ASBMs), and G-RAMM proliferate, defensive approaches that rely solely on expensive, one-time-use interceptors are becoming operationally unfeasible and fiscally unsustainable. The fielding of new technologies that shift this dynamic in favor of the U.S. military could give it a decisive advantage against America's future enemies. Thus, the purpose of this chapter is twofold: to summarize promising DE technologies and to assess the attributes of DE weapons concepts that could confer significant advantages to U.S. forces operating in A2/AD environments.

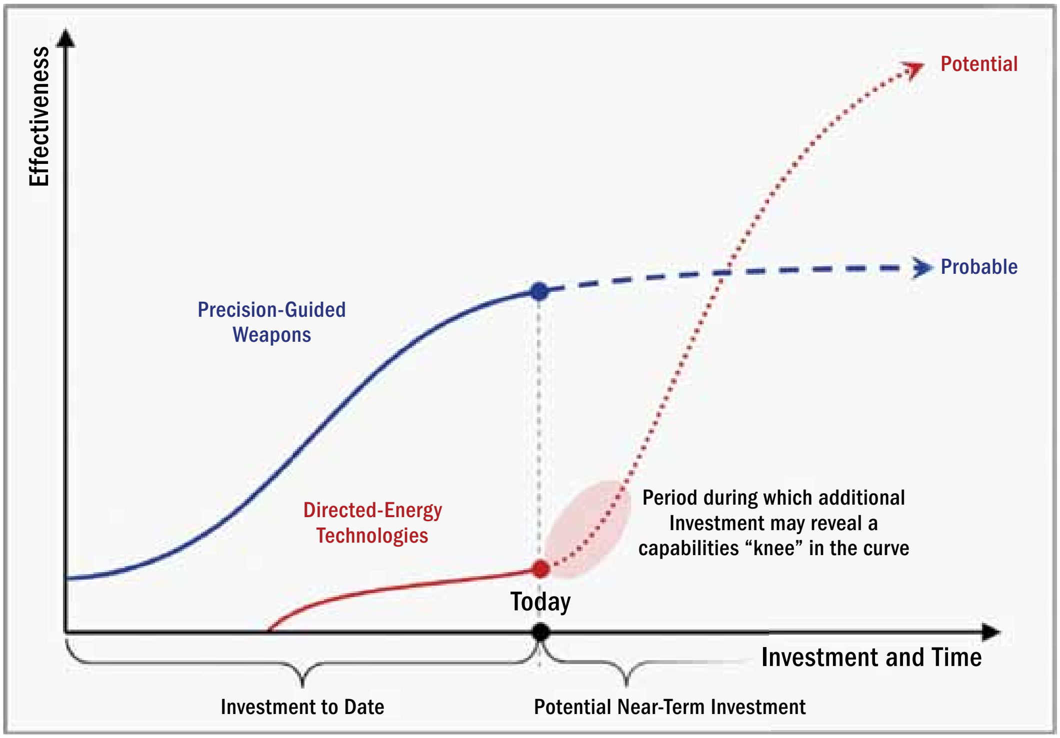
TOWARD A BREAKOUT: EMERGING DE TECHNOLOGIES

As the extended-range, precision-guided weapons regime matures, it is possible that dueling RSCs could reach an operational stalemate. In such circumstances, the United States would have an imperative to field "breakout" capabilities that could lead to major discontinuities in this competition, thereby retaining the U.S. military's freedom of action and enabling power-projection operations.[25] After decades of development, DE technologies have reached sufficient maturity to provide these capabilities and shift the U.S. military toward a more favorable cost-benefit curve (see Figure 1).[26]

[25] Andrew Krepinevich explains that such "discontinuities can be viewed as inflection points, or major shifts in the military competition" that can be "stimulated by several factors, principal among them a combination of new military capabilities, warfighting concepts, and organizational structures that together bring about a military revolution." See Andrew F. Krepinevich, *Defense Investment Strategies in an Uncertain World* (Washington DC: Center for Strategic and Budgetary Assessments, September 2010), pp. 21-22. Clay Christensen, an expert on business innovation, wrote that technologies tend to disrupt marketplaces because they "can become fully performance-competitive within the mainstream market against established products." See Clayton M. Christensen, *The Innovator's Dilemma: The Revolutionary Book That Will Change the Way You Do Business* (New York: Harper Collins, 2000), p. xxvii.

[26] Similar discontinuity curves were suggested by Christensen in Christensen, *The Innovator's Dilemma*, p. xxvii.

FIGURE 1: A NOTIONAL MILITARY TECHNOLOGICAL "BREAKOUT"



A Mature DE Arsenal Could Span the Targeting Chain

Although this chapter emphasizes potential high-power DE capabilities, there is no intent to devalue the utility of low-power DE systems presently fielded or in development. A future DE arsenal will likely include a variety of high- and low-power applications that support military operations across the "find, identify, fix, track, target, and engage" targeting chain.

Since the invention of the first laser, DoD has fielded a variety of low-power DE devices that have proven their value in combat. Perhaps the most famous example is the Paveway laser-guided bomb, developed by the Air Force to strike ground targets in Vietnam with precision.[27] During 1972 and 1973, 48

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27 In one of the most notable examples, a single aircraft with laser-guided bombs took out the Thanh Hoa Bridge in North Vietnam after 871 previous strike sorties using non-precision munitions had failed to do so. The 871 sorties also resulted in the loss of 11 U.S. aircraft. *2003 United States Air Force Directed Energy Master Plan Volume I* (Washington, DC: Headquarters USAF/XPXC, January 2003), p. 1.

FIGURE 2. ILLUSTRATIVE LASER APPLICATIONS

percent of all Paveways dropped around Hanoi and Haiphong achieved direct hits, compared to a little over 5 percent of unguided bombs that struck their intended targets in the same area a few years earlier.[28] By the end of the Vietnam conflict, the Air Force alone had dropped more than 25,000 laser-guided weapons.[29] In more recent years, low-power lasers have been used in a variety of applications, including systems that counter infrared sensors on MANPADS and hand-held, non-lethal systems that "dazzle" personnel who pose a potential threat to ground forces. In the near future, other low-power capabilities could include laser-based networks that provide secure communications for military forces penetrating into non-permissive areas.

While low-power DE applications have proven themselves for more than forty years, maturing technologies for high-power systems could give U.S.

[28] Max Boot, "From Saigon to Desert Storm," *American Heritage Magazine*, November/December 2006, available at http://www.americanheritage.com/articles/magazine/ah/2006/6/2006_6_28.shtml.

[29] See Shelby G. Spires, "Guiding Light," *Smithsonian Air & Space Magazine*, April/May 1999, p. 72. The use of laser-guided bombs also allowed pilots to strike targets with great accuracy while remaining at altitudes that reduced the risk of being hit by ground-based threats.

forces new advantages that span the entire targeting chain (see Figure 2).[30] For example, high-power microwave weapons could be used to target and degrade or destroy the electronic components of A2/AD battle networks. New high-energy laser technologies are also on the cusp of powering game-changing weapon systems that could defend forward bases and forces against aircraft, ballistic missiles, cruise missiles, and G-RAMM.

New high-energy laser technologies are also on the cusp of powering game-changing weapon systems that could defend forward bases and forces against aircraft, ballistic missiles, cruise missiles, and G-RAMM.

High-Energy Lasers (HELs)

In contrast to light bulbs that emit "white light" (photons with a multitude of different wavelengths and phases in all directions), lasers produce narrow beams of monochromatic (single-wavelength) light in coherent beams (all photons traveling in the same direction with the same phase). These narrow beams can focus energy precisely on a designated point. There are three primary types of HELs: chemical lasers, also known as gas dynamic lasers; solid-state lasers; and free electron lasers. Beyond differences in the lasing media, each type has fundamental attributes that affect their ability to mature into operational weapon systems.[31] In addition to the actual lasers, target tracking, laser pointing, thermal management, and beam control systems are required to place as much laser energy as possible on a target over operationally relevant distances.[32]

CHEMICAL LASERS

Chemical lasers are the only current DE systems able to achieve the power needed to interdict targets such as ballistic missiles over hundreds of kilometers. As a result, chemical lasers have until recently been the basis for DoD's most mature HEL concepts.

Chemical lasers use exothermic (energy-liberating) reactions of various chemicals in the gas phase to create atoms or ions in excited states within a lasing medium. Since these reactions must occur at very low pressures—typically only

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30 Figure 2 provides a generalized representation of energy levels, or fluence, that are necessary to create desired effects on various targets. Fluence requirements for specific target types are classified.

31 A lasing medium is the material that produces a coherent beam of laser light.

32 Many assume that the raw power at the output of a laser device is an appropriate means of determining its potential lethality. In fact, it is more important to measure the target fluence of a laser, which is defined as the amount of energy that a laser device can concentrate on a desired area (or "spot") on a target over a specific distance. Fluence is a function of a laser device's energy output, a laser beam's wander (or "jitter"), beam quality (how tightly the beam can be focused), and effects of the atmosphere (such as absorption and scattering) on the transmitted beam. A good beam quality is considered to be less than 2.0 times the diffraction limit (DL), while a laser device with a perfect beam quality would have a beam quality of 1.0 times the DL. See "Encyclopedia of Laser Physics and Technology," RP Photonics Consulting, available at http://www.rp-photonics.com/beam_quality.html. By way of example, industrials lasers used for close-in applications such as cutting and welding typically have very low beam quality ratings of 20 or more.

a couple percent of atmospheric pressure—chemical lasers are large devices requiring vacuum pumps, complex chemical management systems, and low-pressure reaction chambers contained inside a laser resonator.

While there are several types of chemical lasers, DoD used chemical oxygen-iodine lasers (COIL) for the Airborne Laser (ABL) and Boeing's Advanced Tactical Laser (ATL) developmental programs.[33] COILs are capable of generating megawatt-class beams at high efficiencies with good beam quality. The ABL was designed to use a COIL-based weapon system capable of generating the megawatts of power needed to reach across hundreds of kilometers to destroy ballistic missiles in their boost phase of flight, and to do so in a few seconds. Each of the ABL's six lasing modules was the size of a large sport-utility vehicle and weighed more than two tons. The complete laser system weighed more than ninety tons, necessitating the use of one of the largest aircraft in the world, the Boeing 747-400F, to carry it. The developmental ATL used a smaller COIL mounted in a C-130 aircraft to evaluate the potential of an airborne HEL to conduct tactical strikes against stationary and moving ground targets. Although the ATL's COIL energy output was less than 5 percent of that projected for the ABL, it occupied more than two thirds of a C-130's cargo area.

A third developmental chemical laser system—the now-cancelled Tactical High Energy Laser (THEL)—used a deuterium fluoride (DF) chemical laser. While the THEL destroyed more than fifty in-flight rockets, artillery, and mortar rounds during tests, the prototype system occupied five large shipping containers on a 10,000-square-foot pad.[34]

Although DoD has spent billions of dollars on prototype chemical lasers, their large volume, weight, and finite chemical magazines limit the near-term potential to mount them on mobile platforms such as aircraft and ground vehicles. For instance, an aircraft equipped with a COIL would have to land to reload after expending the chemical "fuel" used to create a laser beam. Moreover, since targets located at greater distances require longer laser dwell times (and hence require the laser to use more chemical fuel), shots available per sortie would decrease significantly the further the aircraft was required to stand off from its target area. Finally, the strict purity requirements and highly toxic and corrosive natures of chemical laser fuels would necessitate the deployment of a sophisticated logistics infrastructure to sustain operations at forward locations.

The U.S. Air Force has made great progress toward improving the power and efficiency of COIL modules while reducing their overall size, weight, and

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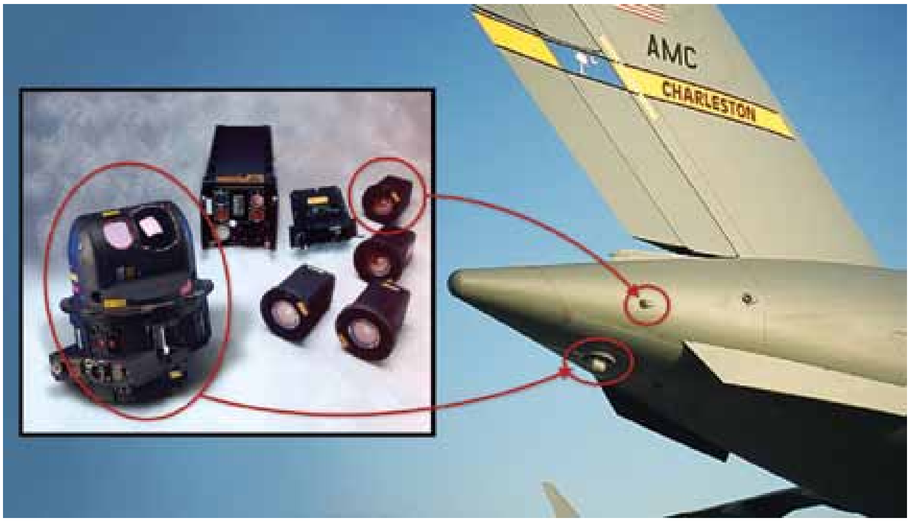
[33] Hydrogen fluoride (HF)-based chemical lasers were considered for space-based laser applications in the 1980s and 1990s, while the Army explored the potential of deuterium fluoride (DF) chemical lasers in its terminated Tactical High Energy Laser (THEL) program.

[34] See "Truck-borne laser to be on way soon," *United Press International*, July 28, 2010, available at http://www.upi.com/Business_News/Security-Industry/2010/07/28/Truck-borne-laser-weapon-to-be-on-way-soon/UPI-31071280342692/.

FIGURE 3. LAIRCM ON AN AIR FORCE C-17



supporting logistics needs. With adequate support and resources, this effort could lead to a new generation of lasers that are suitable to defend forward bases, critical fixed infrastructure, and regional chokepoints such as the Strait of Hormuz against a range of threats (see Chapter 3).

SOLID-STATE LASERS

The first laser invented in 1960 was an SSL. Today, low-power SSLs with outputs of milliwatts are used in a wide variety of consumer products, such as DVD players and laser jet printers. Watt-class SSLs are used in numerous military applications, including target range finders (laser radars, also known as ladars), imagers, target designators, and DoD's Large Aircraft Infrared Countermeasure (LAIRCM) defensive system (see Figure 3).[35]

SSLs use ceramic or glass-like solids, rather than a gas, as their lasing media. There are three SSL types based on the shape of their lasing media: bulk lasers, which use thick doped slabs of lasing media; fiber lasers, which use single or multiple strands of doped lasing fibers that look like common optical fibers;

[35] The LAIRCM was designed to counter MANPADS that are guided by infrared sensors.

and thin-disk lasers, which use glass-like doped disks about the size of a dime.36 Unlike chemical lasers, SSLs do not need expendable chemical fuels and can use nearly any source of electrical power, including batteries, aircraft generators, and ship power plants, to create beams of laser light.37 The outputs of individual SSLs can be combined to generate a single, higher-output laser beam.

Solid-State Slab Lasers. The first high-energy SSLs used bulk lasing media. While early bulk SSLs had very low "wall-plug" power efficiencies, newer bulk SSLs are showing significant promise.[38] For example, bulk SSLs developed by the Joint High Power Solid-State Laser (JHPSSL) program led by DoD's High Energy Laser Joint Technology Office demonstrated outputs of over 100 kilowatts and wall-plug efficiencies of up to 19 percent with long run times. The Defense Advanced Research Projects Agency (DARPA) is pursuing a developmental SSL called the High Energy Liquid Laser Air Defense System (HELLADS):

> The goal of the HELLADS program is to develop a 150 kilowatt (kW) laser weapon system that is ten times smaller and lighter than current lasers of similar power, enabling integration onto tactical aircraft to defend against and defeat ground threats. With a weight goal of less than five kilograms per kilowatt, and volume of three cubic meters for the laser system, HELLADS seeks to enable high-energy lasers to be integrated onto tactical aircraft, significantly increasing engagement ranges compared to ground-based systems.[39]

Fiber Lasers. Similar to slab lasers, it is possible to combine the outputs of single fiber lasers to achieve higher power outputs. Single fiber lasers have achieved a

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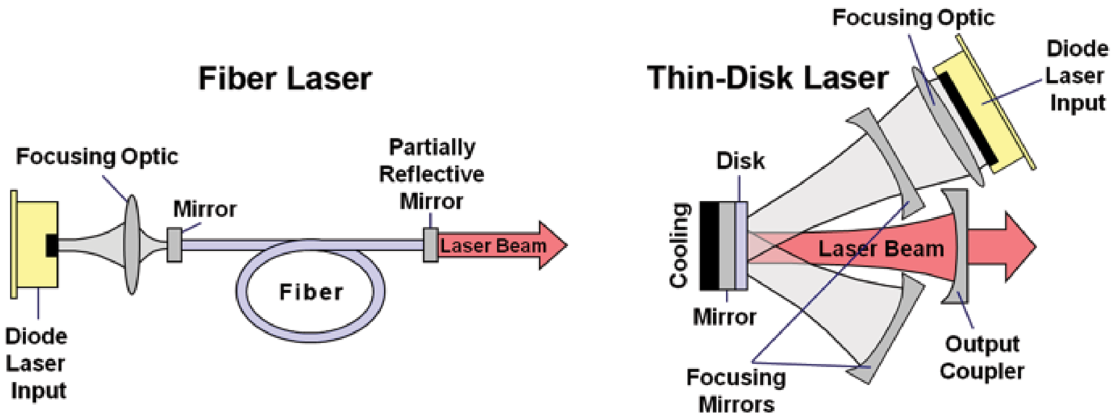
[36] The most common high-power SSL lasing species is neodymium (Nd), a rare earth element. It is "doped" (added) in concentrations up to approximately 3 percent into a glass-like gain medium of yttrium aluminium garnet (YAG). Neodymium-doped YAGs (Nd:YAG) emit 1.064 micron infrared light which is transmitted well through the atmosphere. High-power YAGs containing ytterbium (Yb), the second most common dopant, emit at 1.03 microns. Other promising lasing species include erbium (Er), thulium (Tm), and holmium (Ho), which emit at 1.6 microns, approximately 2.0 microns, and at 2.1 microns respectively. These wavelengths are of great interest since they are more eye-safe than Nd:YAG lasers.

[37] All current SSL tactical platform concepts would use rechargeable batteries to ensure the near-continuous availability of power. Batteries could be recharged following engagements using platform-generated electricity.

[38] The term "wall-plug efficiency" is used to describe the ability of a laser system to convert electricity input to a laser system and then to an optical power output. For example, a laser system with a wall-plug efficiency of 10 percent would require 100 kilowatts of input power to generate a 10-kilowatt laser output. The other 90 kilowatts would be converted to waste heat. See "Encyclopedia of Laser Physics and Technology," available at http://www.rp-photonics.com/wall_plug_efficiency.html.

[39] See the HELLADS description provided by DARPA's Strategic Technology Office, available at http://www.darpa.mil/Our_Work/STO/Programs/High_Energy_Liquid_Laser_Area_Defense_System_(HELLADS).aspx

FIGURE 4. OPTICAL COMPONENTS OF FIBER AND THIN-DISK LASERS



maximum output of a few kilowatts.[40] A Raytheon-Sandia National Laboratory test conducted in June 2006 used an off-the-shelf 20-kilowatt commercial welding laser with very poor beam quality that combined the outputs of many fiber lasers to detonate a stationary 62 millimeter mortar round at 500 meters.[41] It is possible that future systems with multiple fiber lasers could achieve power outputs in the hundreds of kilowatts. Several ongoing DoD and industry research and development efforts are focused on coherently combining the outputs of fiber lasers.

Thin-Disk Lasers. Thin-disk laser systems have produced up to 3.4 kilowatts using four disk lasers in a single resonator. Although this class of SSLs promises a significant reduction in laser weight compared to chemical lasers, thin-disk lasers typically require far more optical components (see Figure 4) and are thus more complex.

Free Electron Lasers (FELs)

Free electron laser (FEL) systems accelerate beams of electrons to nearly the speed of light in racetrack-like accelerator rings and use powerful magnets to "wiggle" the electron beams to generate high-energy beams of laser photons. FELs are of interest to the Navy due to their potential to achieve the high power outputs needed to interdict hardened targets such as incoming ballistic missile reentry vehicles, and their unique ability to "tune" their beams to different

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40 The theoretical maximum output for a single fiber laser is approximately 10 kilowatts.

41 Laser systems with poor beam quality, such as those used in industrial applications, are not useful for targets located more than a couple of kilometers away.

wavelengths to different wavelengths so they can better transmit through the dense, humid atmospheres of maritime environments.[42]

Current developmental FELs are extremely large and inefficient. A FEL at the Department of Energy's Jefferson Laboratory, which has demonstrated an output of 17 kilowatts at 1 percent efficiency, is nearly 240 feet long and 40 feet wide. Over time, it is likely that the overall size of FELs will decrease as technologies for their electron sources and accelerators mature.[43] The U.S. Navy is interested in developing technologies that could lead to a FEL with megawatt-class output levels in the 2020s.[44] Multi-megawatt-class FELs may eventually achieve wall-plug efficiencies of 5 to 10 percent. While better than today's FELs, these systems would still present considerable challenges in terms of the thermal loads placed on ship systems and the shielding required to protect ship systems and personnel.

High-Power Microwave Weapons

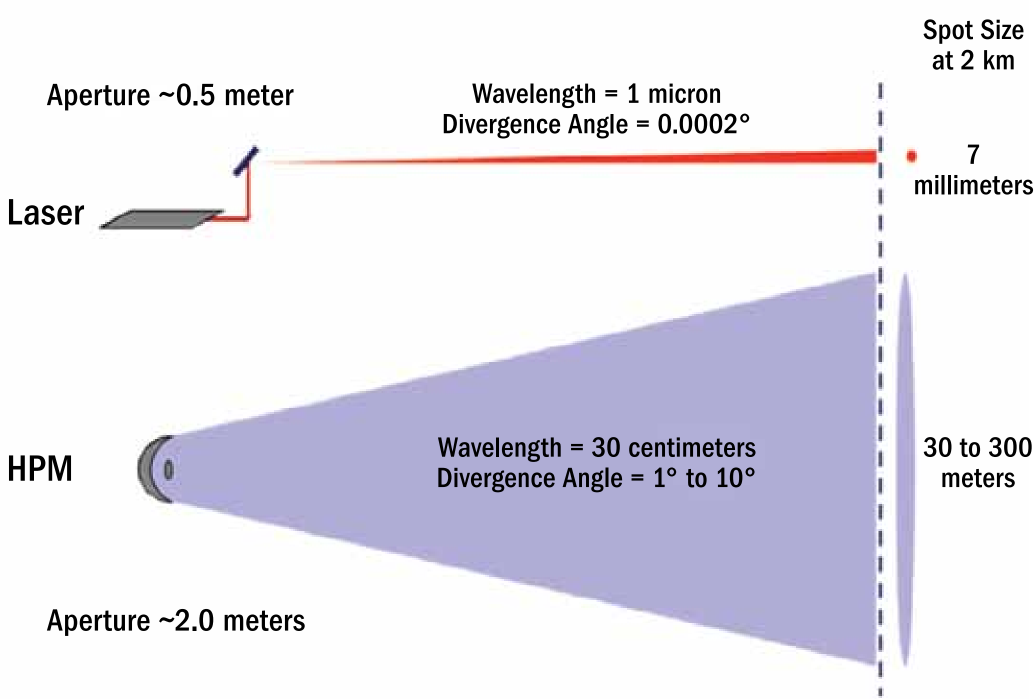
A high-power microwave weapon uses electricity to power a microwave generator that emits very short pulses—typically nanoseconds to microseconds in duration—of microwave radiation at megawatt to gigawatt output levels. Future HPM weapons could emit beams of radiation that are a few degrees wide to attack targets in specific locations or emit radiation multi-directionally to degrade electronic components over wider areas. The effects created by HPM applications could range from temporarily disrupting electronic systems such as computers to physically burning out systems that are not shielded against the

[42] Particles and water vapor suspended in the atmosphere absorb and scatter various laser wavelengths. These effects are greatest at sea level and close to water. "Atmospheric windows" where certain wavelengths are absorbed or scattered very little do exist, but these windows change as environmental conditions change. The ability to "tune" a laser's outputs to these windows can enable the best beam to be transmitted through the atmosphere. See Vasileios Bouras, *High Energy Lasers for Ship-Defense and Maritime Propagation* (Monterey, CA: Naval Postgraduate School, 2002), pp. 3-5.

[43] The technological maturity of developmental FELs is currently rated as between Technology Readiness Level (TRL) 2 and 3. DoD describes TRL 3 as "active research and development is initiated. This includes analytical studies and laboratory studies to physically validate analytical predictions of separate elements of the technology. Examples include components that are not yet integrated or representative." See "Technology Readiness Levels and Their Definitions," p. 1, available at https://acc.dau.mil/CommunityBrowser.aspx?id=23170. The U.S. Navy's Office of Naval Research has estimated that a future 100-kilowatt FEL demonstrator may be as small as 20 to 30 meters long.

[44] Kelley Vlahos, "Navy Breaks World Record With Futuristic Free-Electron Laser," *Fox News*, February 20, 2011, available at http://www.foxnews.com/scitech/2011/02/18/navy-breaks-world-record-futuristic-laser-getting-real/.

FIGURE 5. ILLUSTRATIVE SPOT SIZES OF LASER AND HPM WEAPONS



high electromagnetic fields generated by an HPM pulse.[45] Since HPM beams cannot be as tightly focused as lasers, the energy per unit area in HPM beams decreases significantly over distance. This could impose significant operational limitations compared to longer-range laser weapons (see Figure 5).[46]

Since HPM weapons would affect all unshielded electronic systems within their beam spots, care must be taken when employing them to avoid collateral damage to nearby friendly systems.

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45 In other words, HPM weapons could generate pulses of energy that "overwhelm the ability of a target to reject or disperse RF [radio frequency] energy," and do so without creating effects that would be lethal to humans, thus reducing the potential for unwanted collateral damage. Captain William J. McCarthy, *Directed Energy and Fleet defense: Implications for Naval Warfare* (Maxwell Air Force Base, AL: Air War College, 2000), p. 23, available at http://www.dtic.mil/cgi-bin/GetTRDoc?Location=U2&doc=GetTRDoc.pdf&AD=ADA425498. Also see the U.S. Air Force "High Power Microwave" fact sheet, available at http://www.kirtland.af.mil/library/factsheets/factsheet.asp?id=15869.

46 In fact, a 2007 Defense Science Board task force on directed energy concluded that "the decay with distance of HPM field strengths demands that this system must get within about 10 meters of the target limiting effectiveness in many relevant situations." See Office of the Undersecretary of Defense for Acquisition, Technology, and Logistics, "Defense Science Board Task Force on Directed Energy Weapons," December 2007, p. 35, available at http://www.acq.osd.mil/dsb/reports/ADA476320.pdf.

Non-Lethal Directed-Energy Weapons

Non-lethal directed-energy capabilities have been proven to be safe, legal, and treaty-compliant means of supporting area denial, crowd dispersal, static security, and other related missions. DoD's Joint Non-Lethal Weapons Program is pursuing promising DE technologies to complement the kinetic non-lethal weapons inventory.[47] Non-lethal anti-personnel DE systems, such as optical disruptors (dazzling lasers) and acoustic hailing devices, are currently available to warfighters. Promising new non-lethal capabilities include the Active Denial System (ADS), which uses a focused millimeter-wave beam to create a "push, shove, or repel" effect through a harmless heating of the surface of a person's skin. Research is also underway on the potential to use radio frequency energy to stop ground vehicles and small vessels without lethal effects to their operators and passengers.

UNIQUE ATTRIBUTES OF DIRECTED-ENERGY WEAPONS

The attributes of DE technologies make them promising candidates to "jump the curve" and provide the U.S. military with new advantages over capable enemies during future power-projection operations.

CREATING ADVANTAGES IN TIME

All DE applications transmit electromagnetic radiation in the form of photons that travel at the speed of light.[48] Thus, when an operator fires a DE system, the energy needed to create a desired effect can reach a target almost instantaneously. For example, a high-energy laser weapon integrated with a ship's anti-air warfare defensive systems could engage an incoming cruise missile while it is kilometers away in less than a millisecond and maintain its focus on the missile to destroy or disable it within a few seconds. This engagement speed would make it possible for a single DE defensive system to engage several incoming aircraft, missiles, mortar shells, or artillery rounds in a very short period of time to protect ships, forward operating locations, and troops in the field. Such a capability would be particularly valuable against adversaries employing salvo attacks of ASCMs or G-RAMM to saturate U.S. defenses. Moreover, high-power DE systems could conceivably defeat multiple air and missile threats before an enemy could employ countermeasures to avoid an intercept.

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47 The Joint Non-Lethal Weapons Program is led by the Commandant of the Marine Corps, DoD's Non-Lethal Weapons Executive Agent.

48 The speed of light varies depending on the media through which photons (particles of light) are traveling. In a vacuum, the speed of light, c, is defined as approximately 186,300 miles per second.

CREATING ADVANTAGES IN MAGAZINE DEPTH

The magazines of electric DE weapon systems could be nearly infinite compared to the number of kinetic munitions that are typically carried by U.S. military aircraft, ships, and ground vehicles. This has significant operational implications.

> Electric-powered DE weapons could increase the mission duration of air-refuelable aircraft that currently carry expendable air-to-air and air-to-surface munitions. Similarly, DE weapons could increase the time-on-station of deployed naval vessels, since their "magazines" would not require periodic replenishment at a port facility.

> While it is probable that DE defenses—much like kinetic defenses—could be overwhelmed by ballistic missile salvo attacks, a combination of DE and kinetic systems could increase the number of defensive engagements per salvo attack and thus reduce the potential for enemy missile "leakers" to hit their targets.

> Although surface-to-air and air-to-air munitions will be critical to future U.S. air and missile defense architectures, operational DE weapons with nearly infinite magazines could reduce requirements for mobile weapon systems to carry defensive kinetic munitions. This would enable large combatants, such as naval vessels, to carry additional offensive capabilities.[49]

The magazines of electric DE weapon systems could be nearly infinite compared to the number of kinetic munitions that are typically carried by U.S. military aircraft, ships, and ground vehicles.

The firing rates of future electric laser weapon systems will be contingent on their ability to dissipate the waste heat generated during the production of a high-energy laser beam.[50] For HPM weapons installed in aircraft or cruise missiles, the amount of energy provided by batteries, not waste heat elimination, will determine the number of shots and rate of fire. Because these batteries could be recharged in flight, HPM weapons could have magazines limited only by the endurance of the platforms that carry them.

CREATING FAVORABLE COST-EXCHANGE RATIOS

The recurring cost per shot of DE weapons can be measured by the cost of generating the electricity needed to create their beams. In the case of electric lasers and HPM weapons, this will likely be tens of dollars per shot, far less than the price of

[49] This would also have the effect of reducing strains on logistics networks resupplying deployed forces.

[50] Rapidly removing waste heat is essential because excessive heat can damage components of a laser system.

a PAC-3 missile or similar interceptor.[51] This could reduce the cost of defending against incoming salvos of ballistic and cruise missiles by orders of magnitude. DE weapons could therefore provide the U.S. military with a significant advantage over enemies who remain dependent on more expensive long-range missiles.

CREATING NON-LETHAL EFFECTS

One additional attribute of DE capabilities deserves mention. Future laser weapons could be very precisely focused to permit U.S. troops to engage targets surgically, even in very close proximity to friendly forces or noncombatants. Although HPM beams cannot be focused as precisely as lasers, their potential to counter the electronics of an adversary's weapon systems and infrastructure without harming humans could greatly increase options available to future commanders.

SUMMARY

Innovative technologies have the potential to create significant operational advantages for militaries that are willing and able to exploit them. The unique attributes of future DE capabilities—including their ability to produce precise and tailored effects against multiple targets, their "speed-of-light" responsiveness, and their deep magazines—could allow them to support a wide range of missions and create new opportunities for the U.S. military to gain a disruptive advantage in the emerging precision-guided weapons regime. Simply stated, future DE capabilities could lead to a new military technology "breakout." Moreover, their much lower cost per shot compared to expendable kinetic munitions could help reestablish a cost-imposition dynamic that is favorable to U.S. forces. From a resource perspective, a future DE-enabled U.S. military could reduce its overall requirements to procure, deploy, store, and maintain large inventories of conventional weapons such as ballistic missile interceptors, thus freeing DoD funds for other priority investments.

The next two chapters further assess prospective DE applications and their potential to help create the freedom of action U.S. forces would need during operations against capable A2/AD complexes in Southwest Asia and the Western Pacific.

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[51] For example, it may require two or three gallons of gas, diesel, or aviation fuel to generate the electricity needed to fire an electric solid-state laser. This cost would be negligible if the laser was dependent on energy generated by a ship's nuclear power plant.

CHAPTER 3 > **PROMISING DE CONCEPTS**

The U.S. military has long sought to capitalize on the promise of directed energy. Since the invention of the laser in 1960, DoD has invested more than $6 billion in DE S&T initiatives.[52] While numerous low-energy DE applications have transitioned to programs of record over the last fifty years, only a few high-energy concepts, including the ABL, THEL, and ADS, have made the leap over the "valley of death" between laboratory demonstration systems and working prototypes.[53] Moreover, none of the high-energy concepts that made this leap have become fully operational weapon systems.

Today, high-energy laser, HPM, and non-lethal technologies have advanced to the point where DoD could develop and field DE capabilities that promise to "transform warfighting, enabling revolutionary advances in engagement precision, lethality, speed of attack, and range."[54] This chapter identifies DE concepts that may have the most promise to transition from the laboratory to the battlefield over the next two decades. The concepts proposed in this chapter are based on the maturity of the requisite technologies, not current Service programs.

THE NEXT FIVE TO TEN YEARS

This section describes ongoing and potential technology development efforts that could lead to the fielding of DE applications in the next five to ten years. Although

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52 Estimate from the Office of the Assistant Secretary of Defense for Research & Engineering/ Research Directorate.

53 In other words, the jump from TRL 5 (laboratory demonstrations of integrated system components) to TRL 6 (demonstrations of prototypical weapon systems in relevant operational environments). A full list of DoD TRL definitions is available at https://acc.dau.mil/CommunityBrowser.aspx?id=23170.

54 "Defense Science Board Task Force on Directed Energy Weapons," p. 72.

DoD is currently funding a number of these initiatives, it is possible that many, if not most, will remain at the conceptual level or will be terminated after their initial demonstrations due to the lack of resources and support by the Combatant Commands and Services.

SHIP-BASED SOLID-STATE LASERS

The Navy has funded two significant high-power SSL technology initiatives, the Laser Weapon System (LaWS) and Maritime Laser Demonstrator (MLD), which could lead to new capabilities to counter UAVs, fast attack craft, and potentially ASCMs. LaWS combined six commercial SSLs with a beam director mounted on a Phalanx gun system to produce a 32-kilowatt beam of laser energy. The LaWS demonstrator shot down four UAVs flying over water close to California's San Nicolas Island in 2010.[55] The Office of Naval Research funded development of a second high-power SSL, the MLD, to counter small boats, UAVs and other threats to surface ships. The MLD successfully burned through sections of small boats during static, ground-based firing tests in September 2010, and was mounted on the Navy's Self Defense Test Ship in April and May 2011 for a sea-based demonstration. The MLD package for the latter test used a single 15-kilowatt SSL chain from OSD's JHPSSL program that was tied into the ship's power and radar systems.[56]

The U.S. Navy could field an operational, ship-based laser weapon by 2018

The Navy has also funded two additional SSL concepts. The first concept was designed to explore the potential of a tactical SSL to counter "multiple surface and air threats … such as small boats and UAVs" in various sea states.[57] Work continues to integrate this Tactical Laser System (TLS) with the Mk 38 Machine Gun System. The second SSL concept would integrate a 25-kilowatt fiber SSL onboard an H-60 helicopter to engage surface targets from the air.

The U.S. Navy could field an operational, ship-based laser weapon by 2018 based on technologies demonstrated by the LaWS and MLD programs, both of which achieved Technology Readiness Levels (TRL) between 5 and 6 (i.e., model or prototype demonstrated in a relevant environment). Surface ships are particularly well-suited to support the size, weight, power, and cooling requirements of current-technology SSLs. Flight III of the *Arleigh Burke*-class of guided missile destroyers (DDGs), for example, will have the potential to generate enough excess power and cooling to support a JHPSSL-derivative slab laser system with an output of 100–200 kilowatts (see Figure 6).[58]

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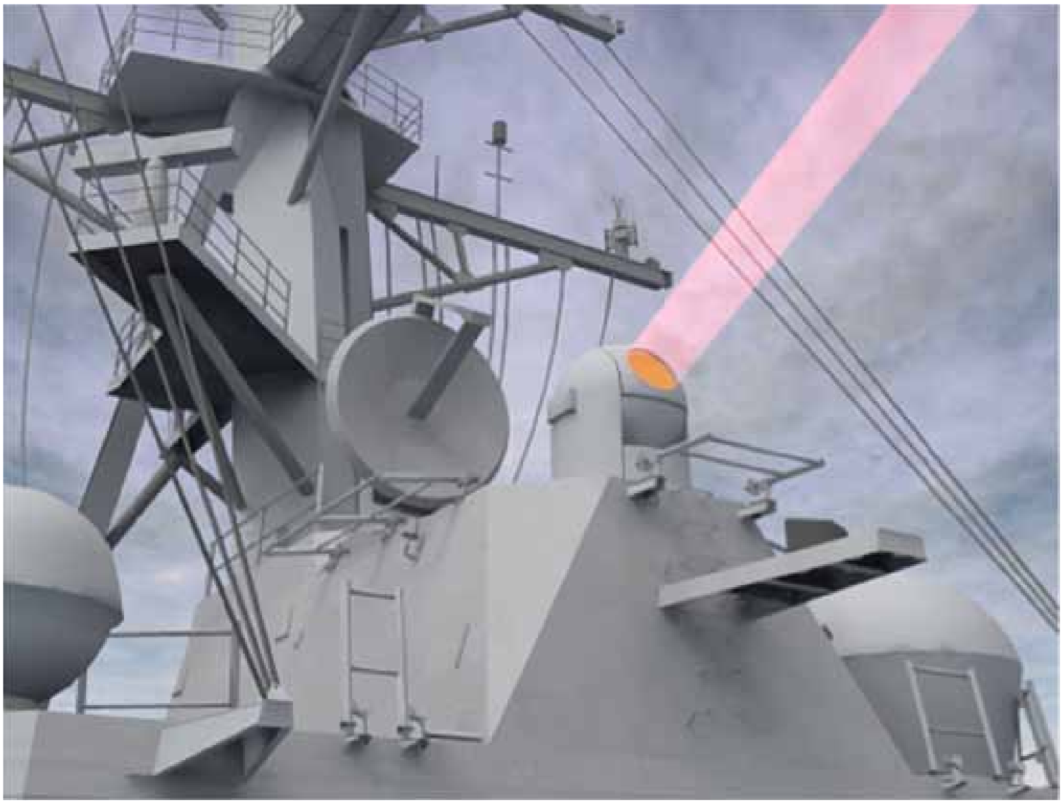
55 See Larry Greenemeir, "U.S. Navy Laser Weapon Shoots Down Drones in Test," *Scientific American*, July 19, 2010, available at http://www.scientificamerican.com/article.cfm?id=laser-downs-uavs.

56 The Maritime Laser Demonstrator, which is based on a laser developed by the JHPSSL program, has an excellent beam quality rating of approximately 1.2.

57 See "Directed Energy Systems," Boeing Defense, Space & Security Backgrounder, September 2011, available at http://www.boeing.com/defense-space/ic/des/index.html.

58 This is drawn from an analysis completed by Northrop Grumman in February 2011.

FIGURE 6. NOTIONAL SSL BEAM DIRECTOR ON A DDG



Fitting *Arleigh Burke*-class DDGs and other surface ships with SSLs could provide the Navy with a globally deployable network for countering attacks by surface craft, UAVs, and possibly ASCMs, especially if the SSLs are used in conjunction with tactics that enable side-shot engagements against incoming missile threats.[59] Moreover, ship-based SSLs could be fired almost continuously, assuming their power supplies and cooling are not interrupted.

Although both the LaWS and MLD demonstrator programs exhausted their funding in fiscal year (FY) 2011, the Navy may soon commit to providing the resources necessary to operationalize an SSL for maritime defense. Given adequate resources, the Navy could become the first Service to field a high-power DE capability that could be the harbinger of a discontinuous shift in the military

[59] The energy needed to counter ASCMs is under debate in the Navy. As previously noted, SSLs with 100–200 kilowatts of output power may be effective against incoming ASCMs if the laser is positioned to achieve a side shot against the cruise missile body. Additional DE lethality testing is needed to help determine an effective energy threshold for a counter-ASCM DE weapon.

competition between guided munitions and the systems designed to defend against them.

LASERS TO DEFEND HIGH-VALUE THEATER BASES

In the near term, it may be feasible to exploit mature technologies to field a ground-based laser weapon capable of defending forward operating locations against air and missile threats. If employed in combination with a relay mirror system, the range and target set of ground-based lasers could be increased significantly to counter cruise missiles and irregular forces preparing to launch G-RAMM. While the precise energy needed to defeat ballistic missiles is not known, sources suggest that a laser with an output in the multi-megawatt range would be needed.[60] Although it is highly unlikely that a multi-megawatt laser weapon system would be ground mobile in the near term, they could be packaged into transport containers that would be deployable by air or sea to protect high-value facilities such as forward airfields and ports. As mentioned previously, DE air and missile defense systems would not obviate the need for kinetic weapons such as the Army's THAAD, PAC-3, and Avenger systems. They could, however, increase the overall effectiveness of air and missile defense networks as well as reduce an enemy's confidence that its attacks would succeed.[61]

The technologies to support a ground-based laser defense are very mature. With adequate resources, DoD could deploy an initial multi-megawatt system in a few years using technologies demonstrated by the ABL program.[62] The Air Force continues to fund a research effort to advance COIL technologies for future military applications. The Air Force Research Laboratory (AFRL) is making progress toward developing smaller COIL modules that generate a megawatt of power at 50 to 60 percent efficiency. AFRL is also exploring methods to recycle the chemicals used as lasing media by COILs, which could reduce the logistics requirements of a deployed chemical laser weapon. The Air Force could incorporate

[60] While there is uncertainty over laser fluence thresholds required to defend against challenging targets such as ballistic missile re-entry vehicles, the Defense Science Board Task Force reported that a FEL with a power output greater than 1 megawatt "would offer initial laser theater ballistic missile defense capability for the surface Navy that could be integrated into current concepts of operation." See "Defense Science Board Task Force on Directed Energy Weapons," p. 25. Other studies agree with this fluence estimate. A 2005 study concluded "a 5 MW output power capable HEL system in a self-defense role may be also capable of engaging and defeating theater ballistic missiles in the terminal phase." See Sean P. Niles, *High Energy Laser Applications in a Surface Combatant: Terminal Phase Theater Ballistic Missile Defense, Low Atmosphere Propagation, and Free Electron Laser Gain* (Newport, RI: Naval Postgraduate School, 2005), p. 79, available at http://www.dtic.mil/cgi-bin/GetTRDoc?Location=U2&doc=GetTRDoc.pdf&AD=ADA435558.

[61] Operators may also be able to use ground-based DE systems to dazzle enemy airborne and space surveillance assets over a very wide area.

[62] Deuterium fluoride lasers are also mature and could be scaled up to achieve megawatt-class outputs. However, there is no current DoD research into DF lasers, which means the work would have to be restarted should this option be desired.

these smaller, more powerful COILs into deployable systems for ground-based air and missile defense within the next five to ten years.[63]

Ground-based missile defenses using SSLs may eventually be feasible.[64] JHPSSL-based developmental systems may be the most mature concepts, having demonstrated power levels in excess of 100 kilowatts. Further investments could enable scaling of this technology to several hundred kilowatts or potentially well over a megawatt. DARPA's HELLADS could also be scaled to higher powers if it realizes its initial 150-kilowatt power objective.

COUNTER-ELECTRONICS HIGH POWER MICROWAVE ADVANCED MISSILE PROJECT

The Counter-Electronics High Power Microwave Advanced Missile Project Joint Capability Technology Demonstration (CHAMP JCTD), initiated by the Air Force in 2009, is developing an HPM package capable of "degrading, damaging, or destroying electronic systems" that could be carried by small airborne platforms such as cruise missiles or UAVs.[65] The JCTD's objective is to develop several aerial test vehicles carrying HPM weapons and assess their performance.

Assuming the JCTD meets its objectives, it may be possible to field cruise missiles and low-observable UAVs with HPM payloads in the very near future.[66] These weapons could allow commanders to conduct multiple strikes per sortie against the electronic systems that underpin A2/AD complexes, such as command and control networks, target acquisition radars, and surface-to-air missile sites. The follow-on development of an HPM weapon carried by a penetrating UAV could result in a more powerful, recoverable system that could create effects over longer ranges and strike far more targets per mission than smaller cruise missile HPM packages.[67]

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63 Multiple COIL modules were used in the ABL demonstrator.

64 Combining the beams of multiple SSLs to achieve megawatt outputs should be possible if an all-electric laser ground-based system is desired. To successfully design a ground-based laser defensive weapon, it will be important for DoD to understand the amount of fluence a laser system must deliver to all potential targets, including ballistic missiles, in order to defeat them.

65 See "Counter-Electronics High Power Microwave Advanced Missile Project (CHAMP) JCTD," US Air Force Official Solicitation Notice, available at https://www.fbo.gov/index?s=opportunity&mode=form&id=e2daa9dccf59c9887810286dc9909d54&tab=core&_cview=1.

66 Since the effective range of HPM weapons would require employing them in close proximity to targets, platforms that carry these weapons must be capable of penetrating enemy airspace.

67 UAVs could carry higher-power HPM weapons, allowing them to engage far more targets per mission at longer ranges compared to smaller HPM packages carried by cruise missiles. According to Boeing, an HPM's effective radiated power "is dependent on the size of the aperture. The bigger the aperture, the more power you can produce and the more standoff you get." See David Fulghum, "First Look: Electronic Warfare Missile," *Aviation Week and Space Technology*, November 22, 2011, available at http://www.aviationweek.com/aw/generic/story_generic.jsp?channel=awst&id=news/awst/2011/11/21/AW_11_21_2011_p29-395318.xml&headline=First%20Look:%20Electronic%20Warfare%20Missile&prev=10.

TACTICAL RELAY MIRRORS

Tactical relay mirror concepts typically use two beam director telescopes and beam control optics to receive a laser beam from a remote source, "clean up" the beam, and transmit it to targets beyond the line of sight of the source laser weapon. A relay mirror could be mounted on a UAV or suspended from an aerostat to significantly extend the range of airborne and surface-fired laser weapons. Tactical relays would be most appropriate to direct lethal laser energy over short ranges (up to a few tens of kilometers) onto targets in coastal, maritime, and urban areas. These systems could also provide persistent, extremely high-resolution imagery of areas within their field of view when not relaying laser beams, permitting them to be used to find, identify, fix, and track targets at significantly extended ranges. A UAV-based relay mirror system could launch from aircraft carriers to enable ship-based SSLs to achieve side shots against ASCMs (a cruise missile's body is a much softer target than its nosecone), and an aerostat-based relay mirror could enable beyond-line-of-sight attacks on G-RAMM and their launch sites.

In 2006, the U.S. Air Force and Office of Force Transformation provided $40 million to develop a Tactical Relay Mirror System (TRMS) technology demonstrator.[68] Outdoor tests of the prototype system suspended by a crane (see Figure 7) were completed successfully.[69] It is uncertain if the Air Force or another Service will continue to fund the follow-on development of an operational TRMS.[70]

ELECTRIC LASER ON A LARGE AIRCRAFT (ELLA)

The U.S. Air Force is developing technologies that could enable the installation of high-energy SSLs on large aircraft. The operational implications of such a weapon are potentially game-changing.[71] For example, a HEL-equipped, penetrating bomber could, in addition to defending itself against air-to-air and surface-to-air threats, strike a variety of ground targets without the need to expend conventional

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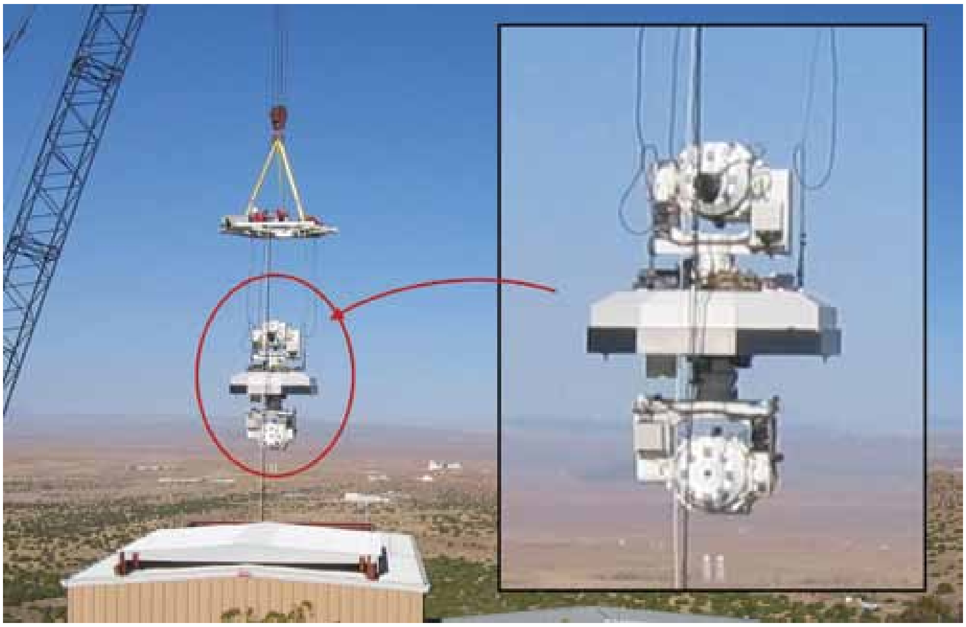
[68] Relay mirrors could use two high-energy laser beam directors coupled with a complex optical bench to receive a beam from an HEL source (such as the Navy's MLD laser) and redirect it onto a target beyond the line of sight of the original HEL. See Boeing, "Directed Energy Systems Backgrounder," available at http://www.boeing.com/defense-space/ic/des/files/DES_overview.pdf.

[69] The TRMS payload is designed for a 60-kilowatt laser. Boeing does not anticipate receiving additional funding from the Air Force to continue development of a tactical relay mirror. Author's discussion with David DeYoung, Boeing's deputy director for directed energy systems, March 1, 2011.

[70] The prototype TRMS is sitting on a pallet at Kirtland Air Force Base in New Mexico.

[71] The Air Force has called ELLA a potential "game-changing" capability that "would open up a raft of new tactical and defensive roles, such as defeating targets that are close to our own troops while avoiding collateral damage to civilians and property, as well as a range [of] rapid-response missions against a whole new set of targets." See Steven Ashley, "Ray Guns Near Crossroads to the Battlefield," *Scientific American*, May 14, 2010, available at http://www.scientificamerican.com/article.cfm?id=ray-guns-near-crossroads.

FIGURE 7. DEVELOPMENTAL TACTICAL RELAY MIRROR SYSTEM



guided weapons. ELLA could also enhance the survivability of air refueling tankers and large command, control, and surveillance aircraft, allowing them to operate closer to hostile airspace to support combat aircraft. It may also be possible for future HEL-equipped air refueling tankers to provide an additional defensive combat air patrol layer for friendly aircraft within the range of their laser weapons, thereby freeing some fighters for other missions.

The Air Force could integrate a 150-kilowatt SSL in the front bomb bay of a B-1B bomber within the next five or six years to test the practicality of this concept.[72] Given the current state of SSL technologies, though, it may not be possible to develop an SSL with an affordable unit cost in the near term that would have sufficient range and power for counter-air missions. With continued funding, however, it may be possible to develop SSL modules that are better suited for both large aircraft in the near term *and* small aircraft in the medium term. Thus, the Air Force should design future combat aircraft, including the Long-Range Strike Bomber, UAVs, and eventually a next-generation fighter, with the potential to accept a laser weapon.

The Air Force should design future combat aircraft, including the Long-Range Strike Bomber, UAVs, and eventually a next-generation fighter, with the potential to accept a laser weapon.

72 "Laser Demo Eyed For B-1B," *Air Force Magazine*, March 25, 2010, available at http://www.airforce-magazine.com/DRArchive/Pages/2010/March%202010/March%2025%202010/LaserDemoEyedforB-1B.aspx. The B-1 module may be derived from DARPA's HELLADs. The demonstrator could take advantage of the B-1's Sniper pod precision-targeting system.

GROUND-MOBILE HIGH-ENERGY LASERS

The Army has long desired a mobile HEL capable of defending on-the-move ground forces against rockets, artillery rounds, and mortars. While fixed-site DE systems could be deployed to defend large theater bases as previously discussed, a mobile system could provide a defense against G-RAMM attacks for maneuver forces and smaller forward operating locations.

Toward this end, the Army began developing the THEL demonstrator in 1996. The Army cancelled THEL development in 2005 because its large footprint made it unfeasible as a mobile weapon system. In 2009, the Army initiated the HEL Technology Demonstrator (HEL TD) program to develop SSL technologies that could lead to a truly mobile laser weapon with an output of at least a few hundred kilowatts to counter G-RAMM threats. HEL TD is developing a compact SSL system with beam control, electrical power supply, thermal management and command, control, and communications elements integrated into a Heavy Expanded Mobility Tactical Truck (HEMTT) with a towed trailer. Although the Army is tentatively planning to develop a mobile HEL by 2018, it has not funded an acquisition program.[73]

The U.S. Marine Corps is also pursuing a future ground-mobile system to replace its legacy kinetic Ground Based Air Defense System (GBADS). The replacement weapon should be capable of countering "Unmanned Aircraft Systems (UAS) with a secondary capability against cruise missiles (CM), manned rotary wing (RW), and fixed wing (FW) aircraft."[74] It is likely that the Marine Corps will assess the feasibility of various SSL technologies as future GBADS weapons during a counter-UAS exercise planned for FY 2012.

GUNSHIP LASER WEAPON SYSTEM

The Air Force Special Operations Command (AFSOC) has expressed a desire for an airborne laser weapon capable of covertly attacking ground targets with great precision over extended ranges. A future gunship aircraft with a suitable laser system may be capable of striking high-value targets with little risk of unwanted collateral damage, a novel capability that would be especially important during operations in urban terrain against irregular forces.

The Advanced Tactical Laser (ATL) Advanced Concept Technology Demonstration (ACTD) was initiated in 2006 to explore the potential of such a capability. The ACTD installed a COIL on a C-130 and successfully engaged

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73 The Army is planning to demonstrate a static SSL in 2012.

74 From the Department of the Navy's official solicitation "USMC Ground Based Air Defense (GBAD) Capability Demonstration," November 21, 2011, p. 1, available at https://www.fbo.gov/index?s=opportunity&mode=form&id=127c451ad456a0ec0657f90d64d71836&tab=core&_cview=1.

FIGURE 8. NC-130H TEST AIRCRAFT WITH THE ADVANCED TACTICAL LASER

representative targets on the ground (see Figure 8).[75] Because of the ATL COIL's size and weight, AFSOC abandoned the concept in favor of exploring the feasibility of replacing one of the AC-130's 20- or 30-millimeter guns with a solid-state laser. Concerns remain over such a system's unit cost and potential to jeopardize other AFSOC modernization priorities, including its plan to recapitalize the aging gunship fleet with new AC-130J aircraft.

NON-LETHAL WEAPONS

Promising non-lethal DE capabilities that could be transitioned in the near term to protect U.S. forces and forward operating bases include radio frequency-based vehicle and vessel stoppers, and an Active Denial System (ADS) that is capable of projecting beams of non-lethal, millimeter-wave energy over tactically relevant ranges to deter hostile acts against U.S. personnel.

A DoD JCTD developed two demonstrator ADS vehicles. The first ADS prototype was mounted on a High Mobility Multipurpose Wheeled Vehicle

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75 See Otto Kreisher, "Gunship Worries," *Air Force Magazine*, July, 2009, available at http://www.airforce-magazine.com/MagazineArchive/Pages/2009/July%202009/0709gunship.aspx. The article reported that the Air Force Scientific Advisory Board concluded that an Advanced Tactical Laser would need "at least 100 kilowatts of power and a seven kilometer slant range to be effective." Also see "Advanced Tactical Laser Aircraft Fires High-Power Laser In Flight," *Air Force News Service*, June 19, 2009, available at http://www.af.mil/news/story.asp?id=123154924.

FIGURE 9. ACTIVE DENIAL SYSTEM NUMBER TWO

(HMMWV) to demonstrate its tactical mobility. ADS version 2 (see Figure 9) was built without size and packaging constraints to provide system hardening against small arms. Both systems underwent extensive testing and demonstrated their ability to create desired non-lethal effects during thousands of "full body shots ... with no personnel injuries."[76] Revised designs could project a smaller beam spot on targets at ranges more desired by warfighters. They could also incorporate newer technologies so they can be mounted on smaller vehicles to enhance force protection and support missions such as humanitarian operations and non-combatant evacuations that could require non-lethal capabilities.

In FY 2011, DoD invested approximately $25 million in non-lethal DE weapon technologies, the vast majority of which was provided by the Joint Non-Lethal Weapons Directorate. While the directorate relies on the Services to transition and

[76] Defense Science Board's Task Force on Directed Energy Weapons, p. 39. The Defense Science Board reported "the ADS has accomplished multiple 'firsts.' It is the first weapon that has successfully completed formally evaluated directed energy counter-personnel Joint Military Utility Assessment, across three separate bases and environments, using twenty different scenarios with multiple iterations. There have been 3,500 full body shots recorded in four field exercises with no significant injuries."

field promising major non-lethal DE capabilities such as the ADS and vehicle and vessel stoppers, the Services have not programmed resources for this purpose.

KILOWATT-CLASS LASER INFRARED COUNTERMEASURES

Multiple Services are in the process of integrating a variety of laser infrared countermeasure systems on military aircraft. Current systems use very low-power pulsed lasers (a few watts) to "jam" or confuse MANPADS guided by infrared seekers. Low-power laser systems such as the LAIRCM and its derivatives may, however, have little effect on advanced MANPADS and air-to-air missiles that use imaging infrared (IIR) seekers and/or multiple seeker systems (e.g., multiple-band IIR, ultraviolet sensors, and passive radar seekers used in conjunction with surface or airborne radars). Using current technology, it should be possible to integrate a kilowatt-class SSL on larger aircraft that could burn out the guidance systems of these more advanced threats.

THE NEXT TEN TO TWENTY YEARS

SHIP-BASED FREE ELECTRON LASER

A future multi-megawatt-class FEL could provide the Navy with a new ship-based capability to engage ASCMs, ballistic missiles, and other airborne threats to surface forces. Ship-based FELs could also be used to defend forward bases located in littoral regions. The Navy's current FEL demonstrator program supports these objectives.

Despite continuing technological advances, it may not be possible to demonstrate an operationally feasible megawatt-class FEL until the mid-2020s or later. Megawatt-class FEL devices will likely remain quite large—potentially spanning multiple bulkheads in current ships—and thus may require new hull designs to accommodate them. Other barriers to creating operational megawatt-class FELs include the massive shielding that would be needed to protect personnel and electronics from the radiation produced by the collisions of stray near-relativistic electrons escaping from the FEL accelerator racetrack,[77] and the challenge of dealing with the waste heat generated by FELs even if they were capable of operating at 5 to 10 percent efficiency.

ELECTRIC LASER ON A SMALL AIRCRAFT (ELSA)

The Air Force is interested in developing a fighter-based laser for counter-air missions. A HEL-equipped fighter could defeat air-to-air and surface-to-air

[77] Author interview with Quentin Saulter, FEL Program Director, Office of Naval Research, March 9, 2011.

missiles launched against it, and greatly extend the fighter's ability to persist in opposed airspace. An ELSA with an output of approximately 200 kilowatts could also prove useful for strikes against soft ground targets.

To be effective, a HEL in a fighter-sized manned or unmanned platform would need to "generate around 5 kilowatts per kilogram [of the laser system's total weight] which means the technology 'has to be reduced in size and weight by a factor of ten over the current ground-based system.'"[78] Given ELSA's potential as a game-changing force multiplier, investments needed to achieve these technological objectives should be a high priority for DoD.

STRATEGIC RELAY MIRROR SYSTEM

The Air Force has explored concepts for mounting relay mirrors on large airships flying at very high altitudes. Strategic relay mirrors carried by airships or high-altitude, long-endurance (HALE) UAVs could enable ground-based or sea-based laser systems to interdict missiles, aircraft, and ground targets across very long ranges.[79] A future strategic relay mirror system could leverage DARPA's Integrated Sensor Is the Structure (ISIS) program, which seeks to develop a very large radar array on an airship that would be able to "detect and track extremely small cruise missiles and unmanned aerial vehicles that are up to 600 kilometers away, dismounted soldiers that are up to 300 kilometers away, and small vehicles under foliage up to 300 kilometers away."[80] DoD is not actively pursuing this concept.

SUMMARY

Directed-energy systems have a reputation as perennial weapons of the future—always showing promise, but technologically out of reach. Today, however, the U.S. military could transition a number of DE technologies to actual battlefield capabilities within five to ten years. Since many of the concepts discussed in this chapter capitalize on decades of S&T investments, DoD should be able to develop and acquire them at lower cost than new "clean sheet" designs. Within the next five to ten years, this includes SSL weapons mounted on surface ships, upgraded COIL modules to defend forward bases, and HPM packages integrated onto penetrating air vehicles. As technological advances continue to reduce the volume,

78 Ashley, "Ray Guns Near Crossroads to the Battlefield."

79 See "Boeing Demonstrates Aerospace Relay Mirror System," Boeing fact sheet, August 7, 2006, available at http://www.boeing.com/news/releases/2006/q3/060807a_nr.html.

80 See "Integrated Sensor Is Structure Program Begins Demonstration Phase," DARPA Fact Sheet, April 27, 2009, available at http://www.darpa.mil/news/2009/ISIS_ph3.pdf.

weight, and cooling requirements of high-power laser systems, it may be possible to integrate them on smaller aircraft and tactical ground vehicles.

Of course, none of the concepts assessed in this chapter will become reality without adequate resources and the support of senior defense leaders who appreciate their game-changing potential in future power-projection operations. It is unlikely that this support will be forthcoming absent an understanding of how DE systems could address future operational needs in a cost-effective manner. The following chapter outlines two plausible scenarios in which DE systems could enable U.S. operations while imposing costs on potential adversaries.

CHAPTER 4 > **CHANGING THE GAME**

To assess how DE capabilities could create new advantages for the U.S. military, Chapter Four examines two notional scenarios that occur ten to fifteen years in the future. In the first scenario, a rogue regional power employs A2/AD weapon systems, including maritime exclusion capabilities, irregular proxy groups equipped with G-RAMM, and ballistic missiles, in a coercive campaign to prevent a U.S. crisis response force from gaining access to the Persian Gulf. The second scenario explores an illustrative AirSea Battle operation against a highly capable A2/AD battle network in the Western Pacific.

In both scenarios, this report assumes the United States will be among the first to operationalize high-power DE weapon systems. As with most innovations in military technologies, however, it should likewise be assumed that other states and non-state actors will gain access to similar capabilities.[81] Therefore, it will be important for the U.S. military to assess the potential of new DE capabilities in a range of scenarios, including cases where enemies have developed similar systems.

SUPPORTING OPERATIONS IN THE PERSIAN GULF

An Illustrative Scenario

Over the next ten to fifteen years, it is likely that Iran will continue to acquire capabilities that will enable the Iranian military and the Iranian Revolutionary

[81] For example, it is known that the PRC is developing laser, HPM, and particle beam weapons for anti-satellite missions. See Office of the Secretary of Defense, *Annual Report to Congress, Military and Security Developments Involving the People's Republic of China* (Washington, DC: Office of the Secretary of Defense, 2011), p. 37, available at http://www.defense.gov/pubs/pdfs/2011_cmpr_final.pdf.

Guard Corps to contest the ability of foreign forces to operate in the Persian Gulf. The following scenario illustrates how Iran might execute an A2/AD strategy in a notional conflict in the 2030 time frame. The scenario assumes that Iran begins hostilities without warning, and that deployed U.S. forces remain reliant on bases in the Persian Gulf region.

AMBUSH U.S. NAVAL FORCES IN THE PERSIAN GULF

Iran could exploit the element of surprise to launch a concentrated, combined-arms attack against U.S. forces operating in the Persian Gulf. Using the narrow and congested waters of the Gulf and Strait of Hormuz to its advantage, Iran could launch multiple UAV and small boat swarm attacks in an attempt to overwhelm the U.S. Navy's kinetic defenses, such as the AEGIS missile defense system, Close-In Weapons System (CIWS), and Rolling Airframe Missile. Iran could augment these attacks with "civilian" vessels equipped with Klub-K missiles stored surreptitiously in shipping containers and shore batteries capable of launching salvos of ASCMs.

ATTACK REGIONAL BASES

In concert with its maritime exclusion operations, Iran could strike U.S. airfields, logistics bases, and ports using short- and medium-range ballistic missiles (SRBMs). By opening its barrage with salvos of older "dumb" missiles, Iran could seek to force the United States to expend large numbers of its kinetic missile interceptors, thereby opening the door for strikes by newer, precision-guided missiles. Iranian-sponsored proxy groups could augment Iran's conventional missile offensive by attacking U.S. bases and critical regional infrastructure using pre-sighted G-RAMM.[82]

CONDUCT A COERCIVE MISSILE CAMPAIGN

Although Iran's large ballistic missile arsenal may lack the accuracy needed to execute a fully effective conventional counter-force campaign against deployed U.S. units, it could be sufficient to support a *counter-value* campaign similar to the "War of the Cities" in the Iran-Iraq war.[83] Iran could launch strikes against regional population centers and key infrastructure to coerce Persian Gulf states to deny the U.S. military basing access and overflight rights. Moreover, Iran could

[82] These proxies may be able to use mobile phone networks or social media to provide Iran with bomb damage assessments (BDA) to determine the need for follow-up strikes.

[83] NASIC, *Ballistic and Cruise Missile Threats*, pp. 11-13; and Steven A. Hildreth, "Iran's Ballistic Missile Programs: An Overview," *Congressional Research Service*, February 4, 2009, p. 3, available at http://www.fas.org/sgp/crs/nuke/RS22758.pdf.

threaten targets in Israel or Southern Europe with longer-range missiles armed with WMD in an attempt to deter a U.S. military intervention in the Persian Gulf.

ATTACK PERSIAN GULF ENERGY AND WATER INFRASTRUCTURE

As part of a campaign to coerce Persian Gulf states to deny basing and overflight access to U.S. forces, Iran could launch missile attacks against Persian Gulf energy infrastructure and water desalination facilities. Iran could also use its proxies to launch G-RAMM strikes on critical government facilities and civilian infrastructure across the Middle East.

DENY PASSAGE THROUGH THE STRAIT OF HORMUZ

Concurrent with its initial attacks against U.S. forces and regional governments, Iran could use sea mines, ASCMs, and fast attack craft in an attempt to control maritime traffic through the Strait of Hormuz. Mine warfare may be one of Iran's primary means of denying passage through the Strait.[84] Though it may hope to sink or severely damage a U.S. Navy vessel, the primary goal of an Iranian mining campaign would be to deny safe access to the Persian Gulf and force the U.S. to engage in prolonged mine countermeasure (MCM) operations under threat from shore-based ASCMs. U.S. MCM ships, which lack the armor and self-defenses of larger warships, would be unable to operate in the Strait until these threats are suppressed.

To further complicate U.S. operations, Iran could deploy multiple ground-based ASCM batteries in camouflaged and hardened firing positions along its coastline and on Iranian-occupied islands in the Gulf. Using targeting data from coastal radars, UAVs, surface vessels, and submarines, Iranian batteries could launch salvo and multiple-axis attacks to saturate U.S. defenses. Similar to its ballistic missile tactics, Iran may choose to withhold its more advanced ASCMs until it is confident that the U.S. military has depleted its most capable kinetic defenses.

DISRUPT U.S. MILITARY NETWORKS

Using its own cyber capabilities or third-party "hackers for hire," Iran could attempt to interfere with U.S. military and civilian computer networks, including the logistics networks that support U.S. force deployment and sustainment operations.

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[84] Iran could employ a combination of "smart" influence mines along with large quantities of less capable surface contact mines. Mines could be dispersed from a variety of surface vessels—including civilian vessels—while submarines are reserved to disperse sophisticated influence mines covertly. See Fariborz Haghshenass, *Iran's Asymmetric Naval Warfare* (Washington, DC: Washington Institute for Near East Policy, 2008), p. 16; and Caitlin Talmadge, "Closing Time: Assessing the Iranian Threat to the Strait of Hormuz," *International Security*, 33, No. 1, pp. 91-92.

Potential Roles for U.S. DE Capabilities

This putative scenario would pose a significant challenge for a future U.S. power-projection force. To open the Strait of Hormuz, U.S. forces would likely need to suppress Iran's air defense systems, defeat its fast attack craft and submarines, counter land-based UAVs and ASCMs, and clear mines while operating from land and sea bases that may lie well outside the range of Iran's missile threats. Moreover, U.S. forces that operate inside the effective range of Iran's A2/AD systems would need to rely on finite inventories of kinetic defenses to counter threats that typically cost a fraction of the price of an SM-3, PAC-3, or THAAD interceptor.

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The DE concepts summarized below could assist U.S. forces to restore their freedom of action in future operations against A2/AD complexes. They could also act as significant force multipliers, expand options available to U.S. commanders, and enable the U.S. military to break out of the current cost-imposing paradigm.

COUNTERING AN IRANIAN BALLISTIC MISSILE CAMPAIGN

A future "DE family of systems" could enable U.S. ballistic missile defense operations across the targeting chain and help restore the U.S. military's ability to operate from forward bases. Offensive ground- and sea-based laser systems could dazzle or blind the sensors used by Iran for targeting and battle damage assessments (BDA).[85] HPM systems such as CHAMP or an enhanced version of CHAMP carried by penetrating manned or unmanned aircraft could suppress the battle networks that Iran needs to target its guided missiles effectively.[86] The Air Force's ELLA program could lead to airborne SSLs powerful enough to reach across significant distances with great precision to interdict missiles in their boost phase of flight before they can reach Persian Gulf states, Israel, or Southern Europe.[87] A future high-power SSL carried on stealthy penetrating platforms could provide the U.S. military with the capability to fly combat air patrols over enemy missile launch areas with a persistence limited only by system endurance and the availability of air refueling.

Directed-energy systems, combined with kinetic weapons, could also create a robust network to defend U.S. forces and bases against air and missile threats. DoD could deploy transportable ground-based chemical or solid-state lasers to defend high-value fixed sites such as air bases, ports, and population centers

[85] By 2030, it is possible that Iran may have developed its own space capabilities or, more likely, will be able to lease satellite coverage from commercial providers or third-party nations.

[86] David A. Fulghum, "Light Boosts Destructive Power of Microwave Weapons, Sensors," *Aviation Week and Space Technology*, January 21, 2007, available at http://www.aviationweek.com/aw/generic/story_generic.jsp?channel=awst&id=news/aw012207p1.xml&headline=null&next=10; and "High-Powered Microwaves," Kirtland Air Force Base, November 18, 2009, available at http://www.kirtland.af.mil/library/factsheets/factsheet.asp?id=15869.

[87] Warwick, "AFRL's ELLA–Getting Electric Lasers Airborne."

concentrated along the western coastline of the Persian Gulf.[88] This could help shift the cost-benefit ratio in favor of the United States and its partners by forcing an enemy to expend large numbers of its ballistic missiles against defenses that have deep magazines and a negligible cost per shot.[89]

COUNTERING THREATS TO SURFACE VESSELS: LASERS AS "MAGAZINE MULTIPLIERS"

In the scenario postulated above, small-boat swarming attacks and multi-axis ASCM salvos could overwhelm U.S. shipboard kinetic defenses such as guided missiles and deck guns. These threats could prove particularly challenging for U.S. MCM ships that typically lack sufficient on-board defenses to counter saturation attacks. Furthermore, the loss of even a small number of low-density/high-demand MCM assets would significantly extend the time needed to clear the Strait of Hormuz, or even halt mine-clearing operations until these ships could operate at reduced risk.[90] By delaying U.S. counter-mining operations, Iran could use time to its advantage, creating the breathing room needed to pursue a regional coercive campaign.[91]

Maritime defenses that integrate kinetic and DE systems could change this dynamic. A 100-200-kilowatt SSL mounted on the deck of an *Arleigh Burke*-class guided missile destroyer (see Figure 10) or similar vessel could engage large numbers of targets in quick succession and counter UAVs used to gather targeting information, thereby permitting MCM ships to operate in the Sea of Oman and Strait of Hormuz earlier in a campaign.[92] Defeating ASCMs with SSLs at these power levels would require the use of multi-ship, area-defense tactics and/or relay mirrors to achieve lethal side shots against the cruise missile bodies. Relay mirrors could also permit a single laser to engage missiles attacking from different directions.

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[88] "Defense Science Board Task Force on Directed Energy Weapons," p. 18.

[89] Ronald O'Rourke, "Navy Shipboard Lasers for Surface, Air, and Missile Defense: Background and Issues for Congress," *Congressional Research Service*, April 8, 2011, p. 3.

[90] Talmadge, "Closing Time: Assessing the Iranian Threat to the Strait of Hormuz," pp. 85, 93-100.

[91] Ibid, p. 115.

[92] Grace V. Jean, "Navy Aiming for Laser Weapons at Sea," *National Defense*, August 2010, available at http://www.nationaldefensemagazine.org/archive/2010/August/Pages/NavyAimingforLaserWeaponsatSea.aspx.

FIGURE 10. ILLUSTRATIVE SSL MARITIME DEFENSE SYSTEM

Linking airborne and surface DE capabilities with the Navy's Cooperative Engagement Capability (CEC) would create a layered and mutually supportive kinetic and non-kinetic defense against swarming and salvo threats.[93] Within the CEC network, DE systems could serve as both precision sensors and weapons, significantly reducing the Navy's use of expensive Harpoon, Hellfire, Penguin, Standard, and Evolved Sea Sparrow missiles. According to the Congressional Research Service:

> 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 … a technological shift for the Navy—a "game changer"—comparable to the advent of shipboard missiles in the 1950s.[94]

93 For a visual representation, see "Defense Science Board Task Force on Directed Energy Weapons," p. 24.

94 O'Rourke, "Navy Shipboard Lasers for Surface, Air, and Missile Defense," p. 3.

TABLE 1. ILLUSTRATIVE LASER-ENABLED ALTERNATIVE DDG LOADOUTS

Missions	Weapons	Baseline Loadout	Alternative 1: Maximize DDG Time on Station	Alternative 2: Maximize Strike Capabilities	Alternative 3: Maximize BMD Capabilities
Anti-Air Warfare	Laser Defenses	0	2	2	2
	SeaRAM CiWs	21 (Deck)	21 (deck)	21 (deck)	21 (deck)
	Evolved Sea Sparrow Missiles	32 (8 cells)	220 (55 cells)	0	0
	Standard Missile 2	40	10	10	10
	Standard Missile 6	34	17	17	17
Ballistic Missile Defense (BMD)	Standard Missile 3	6	6	6	61
Anti-Surface Warfare	Anti-Submarine Rockets	4	4	4	4
Strike	Tomahawk Cruise Missiles	4	4	59	4
	Multiplier	Baseline	x12 Time on Station	x15 Strike Capacity	x10 BMD Capacity

Using high-energy SSLs for maritime defense would have a significant force-multiplying effect. In a Persian Gulf scenario in which an enemy attempts to use swarming tactics to overwhelm U.S. surface ships, it may be impractical to simply shift additional ships to supporting fleet defense at the expense of strike and anti-submarine missions. Moreover, the on-board kinetic defenses of surface combatants, such as DDGs, could be exhausted in a short period of time in high-threat environments, requiring them to leave their combat stations to resupply at a rear-area port facility. In comparison, equipping DDGs with high-energy laser defenses could free their capacity to carry other weapons and significantly extend their time on station (see Table 1).

A future system based on fiber laser technologies developed by the LaWS program, or slab lasers developed by the JHPSSL or DARPA'S HELLADS programs could cost less than $20 million per unit.[95] The cost of acquiring and integrating a ship-based SSL weapon could be partially offset by reducing procurement of expendable kinetic munitions.[96]

Using high-energy SSLs for maritime defense would have a significant force-multiplying effect.

[95] Ibid, p. 10.

[96] As previously mentioned, Standard Missiles cost between $9 million to $15 million, depending on the missile variant. A Rolling Airframe Missile has a unit cost of approximately $800,000, and an ESSM costs about $1.4 million each.

Over the next twenty years, it may also be possible to develop long-endurance manned or unmanned platforms, such as the Navy's future Unmanned Carrier Launched Airborne Surveillance and Strike (UCLASS) aircraft, that are equipped with look-down, shoot-down SSLs to defend the fleet.[97] Compared to ship-based lasers, airborne lasers would suffer far less beam attenuation than ship-based SSLs operating in maritime atmospheres, and may not need tactical relay mirrors to achieve side shots against cruise missiles.

It is important to emphasize that DE defenses would complement, rather than completely replace, kinetic close-in maritime defense systems. For example, small fast attack craft can be difficult to disable or destroy with directed-energy weapons alone, especially if the boats employ smoke or obscurants that can degrade the effectiveness of laser beams.[98] Furthermore, although solid-state DE weapons may have nearly infinite magazines, they are still limited by system cooling requirements and the need to dwell on targets long enough to create desired effects. Thus, it is possible that very large swarms of fast attack craft firing rockets at close range could saturate maritime DE defenses operating without the support of kinetic countermeasures.[99]

COUNTERING G-RAMM

Although mortar and rocket attacks have been a daily fact of life during operations in Iraq and Afghanistan over the past decade, for the most part they have been imprecise. A new generation of guided mortars and rockets could give irregular forces the ability to hit targets repeatedly and with far greater precision. In a future Persian Gulf conflict, state-sponsored proxy forces trained and equipped to use such weapons could wreak havoc against vulnerable targets such as unsheltered aircraft, marshaling yards, fuel depots, and vessels operating in littoral areas. If equipped with advanced MANPADS, irregular forces could threaten air operations in the Gulf, particularly airlifters and helicopters flying "low and slow" while arriving at or departing from forward airfields. Although many of these aircraft presently carry LAIRCM and similar very-low-power DE countermeasures,

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97 The Air Force may pursue "hybrid" laser technology for this application, mixing parts of solid-state and chemical-gas lasers. See David A. Fulghum, "Laser Weapons for Tactical Aircraft," *Aviation Week*, August 18, 2010, available at http://www.aviationweek.com/aw/blogs/defense/index.jsp?plckController=Blog&plckScript=blogScript&plckElementId=blogDest&plckBlogPage=BlogViewPost&plckPostId=Blog%3A27ec4a53-dcc8-42d0-bd3a-01329aef79a7Post%3Ad9b6e121-f73a-4724-a63b-7c02e72a6461.

98 O'Rourke, "Navy Shipboard Lasers for Surface, Air, and Missile Defense," pp. 5-6.

99 Ibid, p. 6. The 200-300-kilowatt solid-state "Directed Energy-CIWS" might be able to interdict munitions fired from swarming small boats, thereby freeing on-board kinetic defenses to engage the boats themselves.

these systems may not be effective against more advanced MANPADS that employ imaging infrared seekers and/or multi-mode seekers.[100]

G-RAMM-equipped proxies would present a difficult operational challenge to future U.S. operations in the Persian Gulf, particularly for military units tasked with defending critical areas such as the ports and cities of regional partners. Unlike ballistic or cruise missiles, the small footprint of G-RAMM weapons allows irregular forces to use them in densely populated environments. Current kinetic defenses such as the Counter-Rocket, Artillery and Mortar (C-RAM) system—which is essentially a CIWS ashore—are magazine-limited and not well-suited for use in heavily populated urban areas despite their use of self-destructing rounds to reduce collateral damage.[101]

Directed-energy weapons used in combination with kinetic defenses could shift the initiative away from irregular forces that employ G-RAMM. To protect larger fixed bases, megawatt-class COIL ground-based defenses could interdict hardened G-RAMM at a cost per shot that would be far less than even the cheapest G-RAMM round. Future mobile SSLs could be small enough to forward-deploy to remote sites or used in rugged terrain to protect maneuver forces.[102] Long-endurance UAVs outfitted with relay mirrors and electro-optical/infrared sensors could support "G-RAMM hunter-killer" combat air patrols operating over U.S. ground forces in coordination with fixed-site COILs or ground-mobile SSLs. These UAVs could enable high-energy laser strikes on G-RAMM sensors, guidance systems, and their operators before attacks are launched, or detonate rounds inflight with a lower risk of causing unwanted collateral damage compared to the use of kinetic defensives.[103]

Directed-energy weapons used in combination with kinetic defenses could shift the initiative away from irregular forces that employ G-RAMM.

ENABLING AIRSEA BATTLE IN THE WESTERN PACIFIC

An Illustrative Scenario

The following scenario illustrates how China might execute an A2/AD strategy fifteen to twenty years in the future. The scenario assumes that China begins hostilities, the United States and its allies lack adequate intelligence and warning

[100] Steve Colby, "The Military Spin: Training for MANPAD Encounters," *Rotor & Wing Magazine*, July 1, 2007, available at http://www.aviationtoday.com/rw/issue/departments/militaryspin/The-Military-Spin-Training-for-Manpad-Encounters_13639.html.

[101] A CIWS is essentially a multiple-barrel gun that can rapidly fire a stream of 20-millimeter shells to provide a close-in "point defense" against threats such as ASCMs.

[102] "Defense Science Board Task Force on Directed Energy Weapons," pp. 2, 14, 19, 28.

[103] Ibid, pp. 13-14.

about a pending attack, and U.S. forces and Western Pacific posture are based on the current defense program projected into the future.[104]

LAUNCHING A FIRST STRIKE AGAINST U.S SPACE AND CYBER INFRASTRUCTURE

At the beginning of hostilities, China could use its DE capabilities and offensive electronic-warfare systems in a coordinated effort to blind U.S. and allied sensor networks. This effort could be complemented by computer network attacks against U.S. and allied networks—both military and civilian—for the purpose of delaying and disrupting a coordinated military response.

DEGRADE OPERATIONS FROM U.S. FORWARD BASES

As China launches a first strike in space and cyberspace, it could simultaneously salvo ballistic missiles and land-attack cruise missiles against U.S. bases located across the Western Pacific. China could use its large inventory of long-range, precision-guided munitions to target specific facilities at these bases, including vulnerable petroleum, oil, and lubricant (POL) storage areas, to reduce the U.S. military's tempo of operations and prevent the deployment of additional forces to the region.[105] As explained in *AirSea Battle,* the PLA could begin an anti-access offensive against the United States by using salvos of missiles carrying submunitions capable of creating a range of effects, such as disabling air defense radars, damaging runways, and destroying unsheltered aircraft on the ground.[106] With U.S. air defenses weakened, follow-on waves of air and missile strikes could significantly degrade U.S. offensive and defensive operations staged from bases in Japan, Guam, and other forward locations.[107]

ATTACK U.S. SURFACE VESSELS

Although the PLA may be unable to completely deny the vast expanse of the Western Pacific to U.S. surface forces, it could seek to significantly increase the risk to U.S. naval operations within this "keep-out" zone. Using land-based ASBMs, air- and submarine-launched ASCMs, and wake-homing torpedoes, the PLA could attack U.S. and allied surface vessels—particularly U.S. CSGs—at

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[104] For example, U.S. aircraft would continue to operate from bases on Okinawa, Guam, and the Japanese island of Honshu. U.S. Navy forces would continue to rely on support from port facilities at Yokosuka on Honshu and Sasebo on the Japanese island of Kyushu.

[105] PLA missile systems are relatively precise compared to Iran's cruise and ballistic missiles.

[106] van Tol, et al., *AirSea Battle*, p. 21.

[107] John Stillion and Scott Perdue, "Air Combat Past, Present and Future," *RAND Project Air Force*, August 2008, Powerpoint Presentation, slides 10, 14.

ranges out to 1,500 nm from mainland China.[108] The U.S. military's ability to project conventional power would be severely constrained should China succeed in preventing Navy CSGs from deploying to within the effective ranges of their aircraft and land-attack missiles. Moreover, PLA anti-surface capabilities could force a large part of the U.S. fleet to engage in defensive maneuvers as opposed to offensive operations.

INTERDICT SEA LINES OF COMMUNICATION

PLA attack submarines and long-range aircraft could interdict sea lines of communication (SLOCs) throughout the Western Pacific that are critical to sustaining U.S. power-projection operations. PLA Navy nuclear attack submarines (SSNs) patrolling sea lanes near Hawaii and in the Indian Ocean could interdict the flow of supplies and reinforcements and compel the U.S. Navy to divert resources to convoy escort and anti-submarine warfare missions.

Potential Roles for U.S. Directed-Energy Capabilities

Although base hardening and improving kinetic missile defenses may help reduce the impact of repeated ballistic missile salvos on U.S. operations in this scenario, such measures would be extremely expensive. Moreover, China could seek to counter these moves by expanding its guided munitions inventories and striking targets that are difficult to harden, such as port facilities. Alternatively, the U.S. military could develop new DE systems that would help reverse this unfavorable cost-imposing dynamic.

ENABLING A BLINDING CAMPAIGN

The PLA's ability to strike U.S. and allied targets across long ranges using ballistic missiles, ASBMs, ASCMs, and UAVs would depend heavily on its ability to "see" over great distances using over-the-horizon radars (OTHRs), space-based sensors, and airborne networks. Conducting blinding operations to destroy or disable these long-haul sensors early in a conflict could be the most critical line of operation in an AirSea Battle campaign.[109] Future DE weapons could contribute significantly to blinding operations in at least two ways.

> First, the U.S. military could use HPM weapons to disrupt or disable enemy land-based OTHRs and airborne sensors. It may be difficult to knock OTHR

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[108] See, for example, Andrew S. Erickson and David D. Yang, "On the Verge of a Game-Changer," *US Naval Institute Proceedings Magazine*, 135, No. 5, May 2009, pp. 26-32; and James Kraska, "How the U.S. Lost the Naval War of 2015," *Foreign Policy Research Institute*, Winter, 2010, pp. 40-41.

[109] For a summary of an illustrative blinding campaign, see van Tol et al, *AirSea Battle*, p. 56.

arrays out of action for prolonged periods using conventional attacks only. HPM weapons could degrade or destroy unshielded OTHR components, as well as temporarily or permanently negate the critical systems airborne surveillance platforms need to perform their missions.[110]

> Second, although the United States has demonstrated kinetic ASAT capabilities, there are distinct advantages to using directed energy to create a range of effects against opposing space-based sensors.[111] At lower power levels, DE ASATs could “dazzle” or temporarily blind space-based sensors and third-nation satellites that are providing imagery to enemy forces. At higher power levels, land-based DE weapons could permanently blind optical sensors, leaving an enemy and its supporters to choose between shuttering their satellite sensors to preserve them for future use, or risk losing them permanently. Laser defenses on Navy surface ships could be used in this role as well, and could be particularly effective against the overhead satellites used to target CSGs.[112]

DE systems could support U.S. counter-missile operations across the entire kill chain during an AirSea Battle campaign.

CONDUCTING A BALANCED COUNTER-MISSILE CAMPAIGN

DE systems could support U.S. counter-missile operations across the entire kill chain during an AirSea Battle campaign.[113] Low-power laser systems could provide secure, low-probability of intercept, and nearly jam-proof airborne data links for passing missile targeting and BDA data to higher echelons of command. As mentioned previously, low- and high-power lasers and HPM devices could degrade or blind enemy long-range ISR sensors and networks, complicating their ability to find and target mobile carrier strike groups. Although PLA strikes against fixed targets are likely to continue despite the best efforts of a layered missile defense network, the PLA’s ability to conduct accurate BDA would be extremely difficult without long-range surveillance. Uncertainty over the effectiveness of its strikes could cause the PLA to waste missiles against targets that have little or no value.

Future DE capabilities could also interdict ballistic missiles in their boost phase. Today, developmental COILs are the nearest thing the United States has to

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110 Fulghum, “Light Boosts Destructive Power of Microwave Weapons, Sensors.”

111 Given the global dependence on satellites for communications, meteorology, and other uses, major kinetic attacks on satellites could have devastating, long-term effects. China’s destruction of a single satellite in 2007 created a massive debris field that will remain in orbit for decades. See Frank Morring, Jr., “China ASAT Test Called Worst Single Debris Event Ever,” *Aviation Week*, February 11, 2007, available at http://www.aviationweek.com/aw/generic/story_generic.jsp?channel=awst&id=news/aw021207p2.xml.

112 Satellites that have a clear line of sight to a surface ship would be within the line of sight of the ship’s laser weapon.

113 “The best way to defend against PLA missile attacks is to destroy them through counterforce operations before they are launched. In other words, ‘kill the archer, not the arrow.’ ” van Tol et al, *AirSea Battle*, p. 38.

a potential DE capability that could reach across hundreds of kilometers to destroy or disable ballistic missiles shortly after launch. Unfortunately, the COIL-based ABL lacked the survivability required to operate close enough to mainland China to engage land-based missiles in their boost phase.[114] A future high-power SSL mounted on low-observable, long-range platforms could conduct combat air patrols within range of missile launch areas. These DE devices may also be capable of disabling missile transporter erector launchers (TELs) on the ground.

By 2030, it is highly likely that advances in power generation, efficiency, and beam quality technologies could lead to SSLs that could be integrated into smaller aircraft, such as a stealthy fighters and UCLASS. DE-equipped UCLASS squadrons could sustain missile-defense combat air patrols with a persistence limited only by the aircraft's system reliability and the availability of air refueling. These UCLASS patrols could also engage both surface-to-air missiles (SAMs) and air-to-air missiles, providing an additional defensive layer for friendly surveillance and strike aircraft.

In terms of effectiveness, coverage, and cost per engagement, DE weapons capable of interdicting ballistic missiles would represent a major step forward for DoD. Combined with kinetic interceptors, DE systems could provide U.S. forward operating locations with a formidable and cost-effective missile defense network.

In terms of effectiveness, coverage, and cost per engagement, DE weapons capable of interdicting ballistic missiles would represent a major step forward for DoD.

COUNTERING IADS

In addition to fielding large quantities of ballistic and cruise missiles, the PLA possesses a sophisticated IADS consisting of advanced long-range SAMs, hardened and deeply buried command and control networks, and long-range aircraft. Advanced SAMs such as derivatives of Russia's long-range S-300/400/500 systems could threaten U.S. aircraft and cruise missiles at significant distances from China's coastline. By 2030, the PLA will likely field a fleet of fourth- and even fifth-generation fighters. Stealthy interceptors, such as the recently unveiled J-20, could contest U.S. air and maritime dominance over critical areas such as the Taiwan Strait.

By 2030, new DE capabilities could help shift the balance in favor of U.S. offensive counter-air operations. Cruise missiles and stealthy unmanned aircraft equipped with HPM payloads could degrade the PLA's command and control networks, radars, and SAM systems, thereby helping penetrating ISR and strike platforms to complete their missions. Bombers could launch large numbers of low-observable HPM cruise missiles to suppress enemy air defenses from secure standoff distances, creating opportunities for other aircraft to conduct penetrating missions. A smaller stealthy UAS with HPM payloads could enhance the

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114 Christopher Bolkcom and Steven A. Hildreth, "Airborne Laser (ABL): Issues for Congress," *Congressional Research Service*, July 9, 2007, p. 9. Refueling the ABL in a potential AirSea Battle scenario could likewise be problematic.

utility and persistence of such attacks. These strikes could be conducted with little prior warning and might impose significant costs on an enemy, especially if each UAS HPM weapon system could strike scores of targets per sortie.

Strike packages and combat air patrols typically require support aircraft, such as air refueling tankers and airborne warning and control systems (AWACS), which are highly vulnerable to SAMs and air-to-air missiles. Solid-state, high-energy lasers onboard these larger aircraft would give them a self-defense capability that could allow them to fly orbits closer to mainland China and thus improve their ability to support penetrating platforms.[115] U.S. surface ships outfitted with lasers of sufficient power, such as an advanced solid-state system supported by tactical relay mirrors, could also provide supporting "bubbles" of security for forward-area air refueling and wide-area surveillance operations.

SUMMARY

In a future Persian Gulf scenario, DE systems capable of countering ballistic missiles, fast attack craft, UAVs, ASCMs, and G-RAMM salvos could help prevent an enemy from conducting a cost-imposing, coercive campaign against the United States and its regional partners. Similarly, DE capabilities could shift the operational initiative in favor of the U.S. military during an AirSea Battle operation in the Western Pacific.

While the U.S. military could partially mitigate the effects of enemy attacks in either region, symmetric responses would not fundamentally alter the emerging unfavorable cost-exchange ratio between enemy offensive systems and U.S. defensive capabilities. For example, each expansion of an enemy's ballistic missile arsenal might require far more expensive U.S. investments in base hardening and kinetic interceptor programs. In the long run, a defensive posture based solely on dispersal, hardening, and kinetic defenses might therefore be operationally ineffective and fiscally infeasible.

Instead of falling into a cost-imposition trap, DoD has the opportunity to develop DE capabilities that will create new operational advantages for future power-projection forces. Moreover, considering the low cost per shot of DE weapons, a DE family of systems could shift the cost-imposition dynamic in favor of the United States.

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115 "Defense Science Board Task Force on Directed Energy Weapons," p. ix.

CHAPTER 5 > BARRIERS TO TRANSITIONING DE TECHNOLOGIES TO OPERATIONAL CAPABILITIES

In 2007, the Defense Science Board Task Force on Directed Energy Weapons concluded that:

> Directed energy offers tremendous promise in improving operational capabilities to conduct certain missions. The potential of these systems is such that the Department should increase the attention paid to the scope and direction of the efforts underway today. Even after many years of development, there is not a single directed energy system fielded today, and fewer programs of record exist than in 2001. This circumstance is unlikely to change without a renewed focus on this important area.[116]

These insights are as true today as they were in 2007. The latest defense budget does not include a single program of record for the full-scale development of a high-power DE weapon and, given continuing pressures on its budget, it will be difficult for DoD to initiate a major DE program in the near future. Understanding why this is so requires an appreciation of the technological, cultural/organizational, and resource challenges that continue to affect the transition of promising new DE technologies to real-world capabilities.

TECHNOLOGICAL CHALLENGES

Over the past twenty years, DoD terminated three high-profile DE programs that over-promised in concept and under-delivered in practice.[117] Practical military applications for chemical HELs, in particular, were limited by their large size,

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116 Cover letter accompanying the "Defense Science Board Task Force on Directed Energy Weapons" report.

117 The three terminated programs were the Tactical High Energy Laser, the Advanced Tactical Laser, and the Airborne Laser.

weight, and supporting logistics requirements. This may no longer be the case. Modern COILs have several times the output of previous devices and could be packaged into deployable systems to defend fixed sites. Similarly, while there is a need to further ruggedize and reduce the size, power, and cooling requirements of high-power SSLs, HEL technologies are sufficiently mature to support the development of new weapon systems in the near to mid term.

IMPROVING SSL TECHNOLOGIES

While SSLs are inherently smaller and lighter than chemical lasers, further increasing their electrical efficiency and reducing the size of the systems needed to cool their lasing media could accelerate their transition to operational capabilities. Power is lost as waste heat between each component of an SSL: between the power source and the pump, between the pump and the lasing medium, and between the lasing medium and the laser output. When any of these components become too hot, their performance degrades—reducing the overall system efficiency—and they can even be damaged.

Recent advances in SSL technologies have demonstrated significant progress toward improving the efficiency and reducing the cooling requirements of high-power SSL systems. SSLs developed by the High Energy Laser Joint Technology Office's JHPSSL program have achieved up to 19 percent wall-plug efficiency at 100 kilowatts of output.[118] DoD research to increase SSL wall-plug efficiency to 30 percent or greater includes efforts to improve the efficiency of the laser diodes that pump the lasing media. In the past, SSLs were "pumped" by flash lamps that emitted a variety of wavelengths and produced considerable amounts of heat that required large cooling systems to dissipate. Today, SSL lasing media are pumped by photons generated by electrically powered laser diodes. As part of this effort, DARPA's Super High Efficient Diode Sources (SHEDS) program has increased the electrical-to-optical efficiency of laser diodes from 50 percent to more than 70 percent. The ultimate goal of this program is to achieve over 80 percent efficiency.[119]

Since size, weight, and cooling requirements are prime determinants of the potential mobility of a high-energy laser weapon, these and other DoD technology initiatives such as DARPA's HELLADS program could, if successful, lead to fully contained DE devices that could be mounted easily on current and future platforms. For example, it is now more a matter of engineering than invention to install current-technology SSLs on Flight III *Arleigh Burke*-class DDGs to defend against UAVs, small boats, and possibly cruise missiles. It may also be feasible to develop modular SSL packages that would give the U.S. Navy's Littoral Combat

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118 From a CSBA discussion with the director of the High Energy Laser Joint Technology Office.

119 These improvements will further reduce cooling requirements and increase laser efficiency.

Ships (LCS) a more robust self-defense capability against air and missile threats. Over time, more efficient (and thus more compact) SSLs might be installed on the Air Force's new long-range bomber and smaller systems such as fighters and the U.S. Navy's UCLASS.

NEED FOR ADDITIONAL DE LETHALITY TESTING

One additional technological challenge deserves mention. In 2007, the Defense Science Board concluded:

> The Department needs an authoritative single source database for directed energy efforts similar to the munitions effects manual for kinetic weapons. Development of meaningful concepts of operations and analyses of military utility require the foundation of credible weapons effects data and assessments.[120]

While DoD possesses a large body of reliable data for non-lethal DE systems like the ADS and laser dazzlers, it still lacks sufficient, reliable data on the effects of high-energy lasers and HPM weapons against a range of threats. During the research phase of this assessment, DE technology experts from every Service, the Office of the Secretary of Defense, and industry emphasized the need for additional DE lethality testing to determine the thresholds required to achieve effects on challenging targets, including G-RAMM, cruise missiles, and ballistic missiles. Such a database could help inform future DE systems requirements and investment decisions.

The Services may be waiting for near-perfect technological solutions to emerge before committing the resources needed to field high-power DE capabilities.

CULTURAL AND ORGANIZATIONAL CHALLENGES

Much has been written regarding the U.S. military's reluctance to adopt new technologies that are unproven on the battlefield. In a 2009 report, CSBA suggested that historically, the Services were most likely to embrace new capabilities when they "solved an important problem at the operational level of war, sustained a way of fighting already integral to that Service, or preserved the Service's dominant sub-cultures."[121]

In the case of DE, perhaps a fourth reason could be added to this list: The Services may be waiting for near-perfect technological solutions to emerge before committing the resources needed to field high-power DE capabilities. For example, the Navy may choose to forego developing an SSL that could be integrated into the fleet in the near term in favor of a FEL that could require another

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[120] "Defense Science Board Task Force on Directed Energy Weapons," pg. xv.

[121] Thomas Ehrhard, Andrew Krepinevich, and Barry Watts, *Near-Term Prospects For Battlefield Directed-Energy Weapons* (Washington, DC: Center for Strategic and Budgetary Assessments, 2009), pp.3-4.

If DE technologies are to jump the developmental "valley of death" to become full-fledged programs, DoD should transition responsibility for their oversight to organizations whose purpose is the acquisition of new capabilities.

twenty years or more of development—and possibly a new hull design—before it becomes operational. With sufficient funding, however, a ship-based high-energy SSL could reach initial operational capability before 2018. Instead of pursuing this option, previous defense budgets favored technologies related to a FEL weapon.[122] While a FEL with an output of a megawatt or greater would provide a significant capability for interdicting ASCMs and potentially ASBMs, absent significant technological breakthroughs, the very large size, thermal management challenges, and shielding required to protect humans and electronics from the stray radiation produced by FELs make them long-shot candidates for practical ship-borne weapon systems for the foreseeable future.[123]

As a second example, the Army desires a highly mobile, ruggedized SSL that could provide ground maneuver units with the means to defend against G-RAMM attacks. Similarly, the Air Force has invested the majority of its DE budget in technologies that could lead to weapon systems for airborne platforms. While an SSL weapon that is sufficiently compact and ruggedized to be truly mobile may be available in five to ten years, the Army and Air Force could immediately take advantage of mature technologies to develop a ground-based, relocatable chemical laser weapon to defend fixed sites. While this weapon would not be fully mobile, it could be deployed by air or sea to provide bases in the Western Pacific and Southwest Asia with significantly enhanced defenses against air and missile threats. The Army, however, has shown little interest in high-energy lasers that are not fully mobile, and the Air Force does not seem disposed toward funding DE technologies that have no potential to be carried by aircraft or cruise missiles.

To overcome institutional desires to hold out for "perfect" systems, it may be useful to acknowledge that DE weapons will *not* be silver-bullet solutions that will completely replace program of record kinetic weapons. In fact, almost all of the DE weapons concepts discussed in Chapter 3 would be most effective when *combined* with kinetic systems to provide greater levels of protection against advanced threats. As with all military weapon systems, DE weapons will have operational limitations, such as a degraded ability to interdict targets through

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122 The U.S. Navy requested $60 million for FY 2012 FEL research.

123 Current experimental FELs have a wall-plug efficiency of approximately 1 percent and could reach efficiencies of 5 to 10 percent. Even if a FEL could be designed with an efficiency of 20 percent, a 1-megawatt output FEL would require 5 megawatts of input power and the capacity to eliminate 4 megawatts in waste heat. Assuming approximately 3.5 tons of air conditioning capacity will cool heat created by 1 kilowatt of excess power, eliminating 4 megawatts worth of heat would require a little over 1,100 tons of cooling. A DDG-51 Flight III could have 1,800 tons of air conditioning capacity. This would be adequate to provide the estimated 1,130 tons of cooling needed for the DDG-51's systems and SPY BMD radar, but would not provide the additional cooling capacity needed for a 1-megawatt FEL with a 20 percent wall-plug efficiency rating. Cooling requirements are derived from a DDG-51 Class Flight IIA SPY-BMD Back Fit Study completed by the naval engineering firm Gibbs and Cox, May 20, 2008.

If DoD is to capitalize on maturing DE technologies, it will need to change investment priorities that remain heavily weighted toward kinetic weapons.

moist air, fog, and clouds.[124] For these reasons, combining DE and kinetic weapons could permit future warfighters to compensate for the operational shortcomings of each system while increasing overall mission effectiveness.[125]

One additional trait of DoD DE technology programs is worth considering: they are all led by S&T organizations, such as the Navy's Office of Naval Research, the Army's Space and Missile Development Command, the Air Force Research Laboratory, and the High Energy Laser Joint Technology Office. These organizations are dependent on science and technology funding lines. Moreover, they are populated with highly trained specialists who are typically rewarded for advancing the *science* of DE, as opposed to fielding operational weapon systems.

With these factors in mind, if DE technologies are to jump the developmental "valley of death" to become full-fledged programs, DoD should transition responsibility for their oversight to organizations whose purpose is the *acquisition* of new capabilities. Acquisition organizations are focused on developing systems to meet known capability gaps as quickly as feasible, and they are rewarded for producing capabilities, as opposed to pursuing a series of research projects.

RESOURCE CHALLENGES

If DoD is to capitalize on maturing DE technologies, it will need to change investment priorities that remain heavily weighted toward kinetic weapons. DoD's missile defense investments illustrate this dynamic. The FY 2011 defense budget requested $10.2 billion to develop and procure kinetic weapons that are intended primarily to defend against air and missile threats. In contrast, DoD allocated a little over 5 percent of this amount—approximately $500 million—for electric laser and HPM technologies that could lead to new systems capable of countering a much wider range of enemy capabilities, including cruise and ballistic missiles, UAVs, advanced IADS, and command and control networks (see Figure 11).[126]

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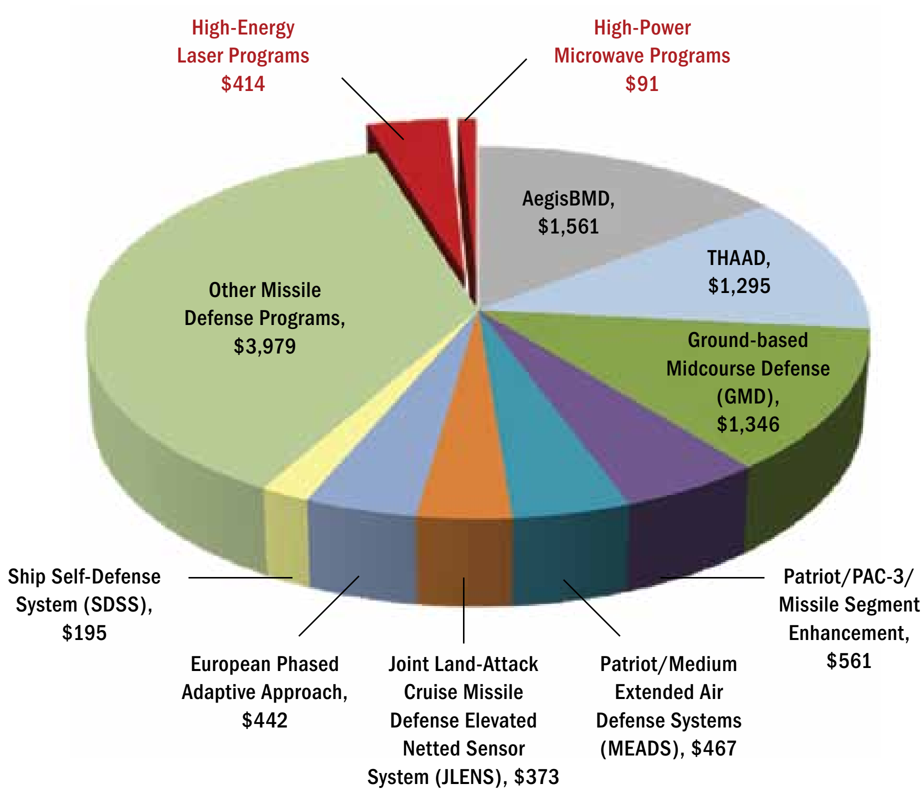
[124] This is much less of a factor for DE weapon systems that operate above 40,000 feet, where there is little weather.

[125] The 2007 DoD Defense Science Board Task Force on Directed Energy concluded as much when it reported that using DE weapons in combination with kinetic systems "enhances the utility of both" and "increases mission effectiveness." See "Defense Science Board Task Force on Directed Energy Weapons," p. 24.

[126] All of DoD's requested DE funding is in three S&T categories: 6.1 (Basic Research), 6.2 (Applied Research), or 6.3 (Advanced Technology Development).

FIGURE 11. FY 2011 FUNDING FOR KINETIC MISSILE DEFENSE AND DE PROGRAMS

(in millions of dollars)



Today, *none* of DoD's DE initiatives are resourced at levels required to transition them to full-scale acquisition programs, nor are prospects particularly good that DoD as a whole will significantly reallocate funding to support DE acquisition programs in the near term. In fact, given downward pressure on the defense budget, some DoD organizations may choose to reduce funding needed to sustain existing DE development. As a result, it is quite possible that a lack of sufficient resources could replace technical challenges and institutional resistance as the most significant barrier to transitioning promising DE technologies to fully operational capabilities.

SUMMARY

Previous DE programs that over-promised and under-delivered created an environment in which DoD is reluctant to move toward to a new generation of potentially game-changing DE capabilities. Barriers to transitioning DE concepts to operational capabilities include technological challenges (which are no longer as daunting as they were in the past), institutional desires to seek "perfect" technological solutions, and insufficient funding.

Three themes emerged during CSBA's discussions with DoD and industry DE experts on how these challenges might be overcome. First, a concerted effort is needed to better inform senior civilian and military defense leaders about DE technologies that have matured to the point where operational capabilities could be developed and fielded within this decade—many within five years. Second, the defense DE community may need a significant "win"—the successful transition of a major high-power DE weapon system to operational status—to prove DE's value to Service leaders and Combatant Commanders. Third, it may require the first use of a high-power DE capability in an event of great military significance, or a DE technology "breakout" by an enemy, before DoD finally grasps its full potential to transform the character of warfare.[127]

The defense DE community may need a significant "win"—the successful transition of a major high-power DE weapon system to operational status—to prove DE's value to Service leaders and Combatant Commanders.

[127] This last point is certainly not without precedent. For example, as noted by distinguished military historian Williamson Murray, it was not until the Blitzkrieg had proven itself during the 1939 invasion of Poland that the German officer corps "as a whole began to grasp the potential of armored exploitation on the operational level of war." See Williamson Murray, "Armored Warfare: The British, French, and German Experiences," in Williamson Murray and Allan Millet, ed., *Military Innovation in the Interwar Period* (Cambridge, MA: Cambridge University Press, 1996), p. 43.

CONCLUSION AND RECOMMENDATIONS

The U.S. military's traditional paradigm of sequentially deploying a large joint force to forward operating locations, rolling back enemy threats, and then conducting decisive combat operations is no longer a particularly useful template for future operations in a maturing precision-guided weapons regime. In such a "post–power projection" world, U.S. forces deploying abroad should instead assume that they will need to fight for their freedom of action in all operating domains. Moreover, relying on increasingly expensive kinetic capabilities to counter an enemy equipped with large quantities of precision-guided weapons will create a cost-exchange dynamic that does not favor the United States. Of greater concern is the possibility that continuing to rely solely on kinetic weapons to counter proliferating threats such as ASCMs, ASBMs, and G-RAMM could lead to scenarios where projecting U.S. forces into harm's way risks prohibitive losses.

The proliferation of precision-guided weapons and other advanced military technologies has already changed the game for future U.S. operations.

Against this backdrop, philosophical debates over whether new technologies may lead to "game-changing" capabilities are of little value. This assessment concludes that it is more important to understand how the proliferation of precision-guided weapons and other advanced military technologies has *already changed the game* for future U.S. operations. In this context, high-energy laser and high-power microwave technologies offer the promise of new capabilities that could enhance the United States' ability to conduct military operations in increasingly challenging threat environments.

Although the advent of mature DE capabilities could significantly change the way the U.S. military conducts future operations, it is unlikely that DE alone will underpin a new military revolution that renders "obsolete or subordinate existing means for conducting war."[128] Perhaps one of the most significant insights developed during this assessment is that DE applications have great potential to com-

[128] Michael G. Vickers and Robert C. Martinage, *The Revolution in War* (Washington, DC: Center for Strategic and Budgetary Assessments, December 2004), p. 2.

plement and significantly increase the effectiveness of kinetic systems, rather than obviate the need for them. Although DE weapons cannot replace kinetic capabilities in the foreseeable future, they have the potential to become powerful new force multipliers and greatly reduce the overall cost of conducting key U.S. offensive and defensive operations. In particular, a combination of non-kinetic and kinetic systems could enable U.S. forces to prevail more rapidly over enemies fielding sophisticated A2/AD weapons. This could create a dilemma for opponents, who could not simultaneously spend enough on offensive weapons to overwhelm the "bubbles" of protection that a layered combination of kinetic and DE systems could extend over U.S. forces *and* field sufficient additional defensive capabilities to counter U.S. long-range surveillance and strike systems. Thus, the fielding of DE capabilities could help the United States buy back its ability to project power at acceptable levels of risk while imposing disproportionate costs on future enemies.

A lack of funding, not technology, are now the most significant barriers to developing major new DE capabilities over the next decade.

There are challenges to overcome before the first generation of high-power DE weapons can be fielded. This assessment concludes that cultural factors and a lack of funding, not technology, are now the most significant barriers to developing major new DE capabilities over the next decade. To overcome these barriers, it may be useful to acknowledge that DE capabilities, which could complement rather than replace kinetic systems, do not pose an existential threat to the Services' most cherished weapons programs. It is also important to understand that waiting until "perfect" DE technological solutions are available could create opportunities for competitors to gain a significant advantage over the United States by fielding their own DE weapons. Sadly, to overcome the barriers elaborated upon above, it may take a catalytic event such as a DE breakout by an enemy before the U.S. military fully grasps that these weapons have become reality rather than interesting science projects.

RECOMMENDATIONS

In lieu of an unfocused strategy in which multiple organizations fund similar directed-energy S&T efforts, DoD should develop an acquisition plan that: (1) focuses its efforts on DE concepts that have the most promise to transition to new operational capabilities over the next decade; and (2) considers the maturity of DE technologies and their system requirements—including size, power, and cooling needs—that would affect their integration with operational platforms. This report recommends that such a plan should include the following initiatives:

> DoD should support the U.S. Navy as the "first adopter" for weaponizing an SSL capable of producing a sustainable 100-plus kilowatt beam of laser energy. Surface ships with sufficient power, space, and cooling are particularly well-suited as platforms for SSLs that could become part of an integrated network to defend against

UAVs, cruise missiles, and fast attack craft. This technology could also transition to support the U.S. Marine Corps' Ground Based Air Defense program and a ground-mobile HEL system for the U.S. Army. This does not mean that the U.S. Navy should forgo some level of its planned investment in higher-risk free electron laser technologies that could eventually lead to new defensive capabilities for countering more challenging threats, such as ASBMs in their terminal phase of flight.

> The U.S. Army and Air Force should leverage mature laser technologies to develop deployable, ground-based, DE defenses against air and missile threats to high-value bases and strategic chokepoints in the Western Pacific and Southwest Asia. It may be advisable for DoD to establish a "competition" fund to support the development and procurement of the most promising concepts.

> DoD should support the U.S. Air Force and Navy as lead Services for developing HPM weapons that could be integrated into mobile platforms such as manned and unmanned aircraft, cruise missiles, and ground vehicles. Unlike state-of-the-art SSLs, HPM systems appear to be sufficiently mature to be weaponized into packages that could be carried by air platforms in as little as three years. The Air Force should continue to pursue technologies that could increase HPM power outputs and ranges, as well as concepts that could lead to recoverable and reusable systems capable of attacking scores of targets per sortie.

> The military Services should work with the Commandant of the U.S. Marine Corps, DoD's executive agent for non-lethal weapons, to transition advanced, non-lethal DE applications being developed by the Joint Non-Lethal Weapons Directorate to programs of record. A more concerted, internal DoD "outreach" effort could improve Service and Combatant Commander understanding of the potential for non-lethal DE capabilities such as the Active Denial System to support future operations.

> Additional lethality testing is needed to substantiate the effects that high-energy lasers and HPM devices can achieve against air, ground, and maritime threats in operationally relevant environments. Near-term testing should prioritize the collection of data on laser lethality against small boats, UAVs, cruise missiles, and ballistic missiles, and the impact of environmental factors such as aerosols, humidity, and obscurants on laser weapons operating in maritime and ground battlefield environments. In 2007, a Defense Science Board task force suggested that "the Deputy Secretary of Defense should assign responsibility to a military department to develop a laser and high power microwave effects manual."[129] This report recommends that a joint entity, such as

Additional lethality testing is needed to substantiate the effects that high-energy lasers and HPM devices can achieve against air, ground, and maritime threats in operationally relevant environments.

[129] "Defense Science Board Task Force on Directed Energy Weapons," pg. xv.

the Office of the Undersecretary of Defense for Acquisition, Technology, and Logistics, may be a more appropriate DoD organization for overseeing the development of a lethality database that would span future DE operating domains and applications.

> Finally, DoD should assess how future DE capabilities could support AirSea Battle operational concepts for the Western Pacific, Persian Gulf, and other regions where emerging A2/AD battle networks threaten the national interests of the United States. Over time, DE systems could become a key element of counter-A2/AD operations while reducing the U.S. military's need to procure costly kinetic weapons that require extensive supporting logistics networks and large forward footprints. In other words, DE could become part of the prescription for how the DoD will deal with the "fiscal realities of limited resources" while creating a new force that "is agile, flexible, deployable, and technologically equipped to confront the threats of the future."[130]

[130] Speech by Secretary of Defense Leon E. Panetta to the Halifax International Security Forum, November 18, 2011, available at http://www.defense.gov/speeches/speech.aspx?speechid=1632.

GLOSSARY

A2/AD	Anti-access/area denial
ABL	Airborne Laser
ATL	Advanced Tactical Laser
ASAT	Anti-satellite
ASCM	Anti-ship cruise missile
AWACS	Airborne Warning and Control System
CHAMP	Counter-Electronics High Power Microwave Advanced Missile Project
CIWS	Close-In Weapon System
COIL	Chemical oxygen-iodine lasers
CSG	Carrier strike group
DE	Directed energy
ELLA	Electric Laser on a Large Aircraft
ELSA	Electric Laser on a Small Aircraft
FEL	Free electron laser
G-RAMM	Guided rockets, artillery, mortars, and missiles
HEL	High-energy laser
HPM	High-power microwave
IADS	Integrated air defense system
ISIS	Integrated Sensor Is the Structure
JHPSSL	Joint High Power Solid-State Laser
LAIRCM	Large Aircraft Infrared Countermeasures

LaWS	Laser Weapon System
MANPADS	Man portable air defense system
MCM	Mine countermeasures
MLD	Maritime Laser Demonstrator
MRBM	Medium-range ballistic missile
OTHR	Over-the-horizon radar
PLA	People's Liberation Army
PLAAF	People's Liberation Army Air Force
PRC	People's Republic of China
SAM	Surface-to-air missile
SRBM	Short-range ballistic missile
SSL	Solid-state laser
THAAD	Terminal High Altitude Air Defense
THEL	Tactical High Energy Laser
TEL	Transporter erector launcher
UAV	Unmanned aerial vehicle
UCLASS	Unmanned Carrier Launched Airborne Surveillance and Strike
VLS	Vertical launch system
WMD	Weapons of mass destruction

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