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DIRECTED-ENERGY WEAPONS:

Promise and Prospects

By Jason D. Ellis

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About the Author

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Cover Images

ARABIAN GULF (Nov. 16, 2014) The Afloat Forward Staging Base (Interim) USS Ponce (ASB(I) 15) conducts an operational demonstration of the Office of Naval Research (ONR)-sponsored Laser Weapon System (LaWS) while deployed to the Arabian Gulf.

(John F. Williams/U.S. Navy)

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PREFACE

By Paul Scharre

Paul Scharre is a Fellow and Director of the 20YY Warfare Initiative at the Center for a New American Security.

Technology is an indispensable component of war. Since the first human picked up a rock in anger, warfighters have leveraged technology to increase their advantage on the battlefield. In modern times, technology has allowed combatants to fight at vast distances, launching missiles across the globe, and has expanded warfare into the air, undersea and into space.

Modern militaries invest heavily in new technologies to modernize their forces, but determining *which* technologies hold the greatest promise is more art than science. It requires militaries to think on multiple levels simultaneously. They must assess the potential utility of a new technology – how much operational or strategic value it will convey. They must weigh the maturity of the technology and the likelihood that their investments will pay off. And they must assess their investments relative to both alternative investments and potential adversary countermeasures that might negate or erode their hard-fought advantages. All of these decisions must be made under conditions of extreme uncertainty and possibly enemy deception. Furthermore, some new technologies – whether novel or proven – applied in combination with new concepts of operation, organization, training and doctrine, can lead to significantly disruptive changes in warfare that alter the very character of how militaries fight and the metrics for what makes weapons useful. Investing in improved stirrups for horse cavalry in the 1920s, for example, would have been a poor use of resources when adversaries were developing tanks that would revolutionize land warfare.

The U.S. military is the most technologically advanced on the planet, and yet it frequently gets these assessments wrong. The list of failed "next-gen" acquisition programs is long and inglorious, and in many cases even sizable investments have proved insufficient to overcome technology limitations or developmental failures.[1] In the current fiscal environment, the Department of Defense

(DOD) must husband its resources closely. DOD cannot afford to place bets everywhere, on every technology area that might show promise. At the same time, the U.S. military's strategic advantage is waning as many of the key technologies that have underwritten U.S. supremacy – precision strike, satellites, stealth and advanced communications, among others – proliferate to others. The U.S. military will have to invest, and invest wisely, in those areas most likely to sustain its competitive advantages in the years ahead.

In the face of these challenges, DOD leaders have declared the search for a "third offset strategy," to follow the two 20th-century "offset strategies": nuclear weapons and precision strike.[2] No single technology or even group of technologies will be a silver bullet for the challenges the U.S. military faces, however. The United States faces too diverse an array of challenges, from terrorists to cyberthreats to nuclear-armed rogue states to near-peer competitors, which require qualitatively different responses and forces. Many of the actions DOD must take to prepare for today's threats center on increasing strategic agility – the ability to adapt rapidly to a changing security environment.

Nevertheless, DOD must also make smart choices about where to invest more than $60 billion annually in research and development. To help identify the most critical technologies, DOD has launched a Long-Range Research and Development Program Plan as part of the new Defense Innovation Initiative.[3] Making the right investments today could help ensure that DOD has both improved capabilities and a greater set of options for out-years acquisition. A failure to invest could forgo those potential advantages or, at worst, cede the advantage in a critical area to others.

Few weapons have held as much promise – and have consistently failed to live up to that promise – as directed-energy weapons. Since the 1960s, DOD has sought directed-energy weapons such as high-energy lasers or high-power microwaves. Directed energy has the potential to yield cost-effective weapons that can deliver precise, scalable effects – and at long ranges – with a large magazine capacity. Actual directed-energy programs, however, have frequently fallen short of expectations. In the 1990s and early 2000s, DOD spent billions in aggregate on high-energy lasers such as the Airborne Laser and Space-Based Laser, both of which ultimately failed to reach maturity. At the turn of the millennium, defense commentators crowed that another "revolution in military affairs," empowered in part by directed-energy weapons, was just around the corner.[4] DOD itself argued that directed-energy weapons were "ready for some of today's most challenging weapons applications, both offensive and defensive."[5] After several decades of investment, billions of dollars and several canceled programs, DOD has yet to successfully field an operational directed-energy weapon system.

Over the past few years, however, even as DOD scaled back its expectations and funding from the highs of decades past, directed-energy technologies have steadily and quietly matured. While more modest in power than the aspirational Airborne and Space-Based Laser programs, today's directed-energy weapons have reached a point of operational maturity. Current-generation tactical lasers have been demonstrated in realistic operational settings against realistic threats. In 2013, the Navy demonstrated the ability of a ship-based tactical laser to shoot down an enemy drone, a more cost-effective counter to low-cost drones than firing a missile.[6] In November 2014, the Navy demonstrated a laser weapon at sea against enemy small boats, a scalable and cost-effective countermeasure to a dangerous threat.[7] The Air Force demonstrated in 2012 the feasibility of airborne high-power microwave weapons. Such technologies have matured to the point where an operationally relevant payload can be carried on a cruise missile or drone, potentially providing commanders a unique nonkinetic capability to disable or destroy enemy electronic systems.[8]

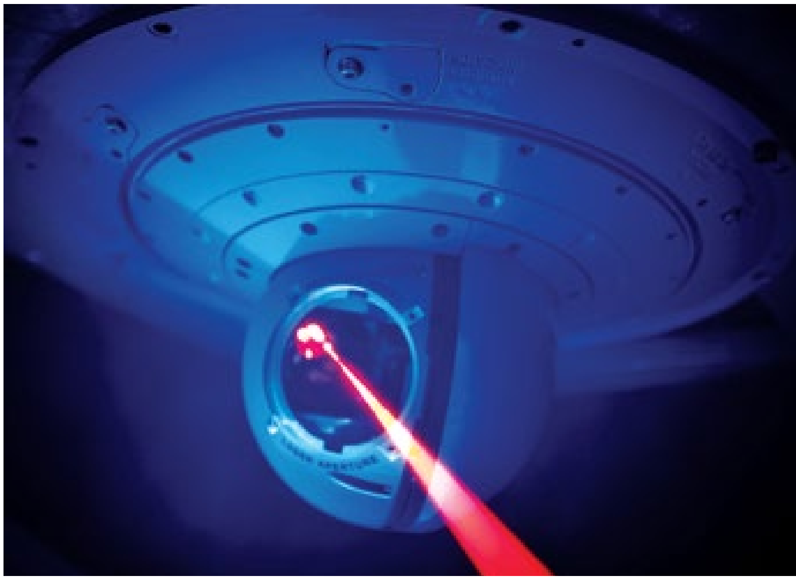


Photo of Large Aircraft Infrared Countermeasures System (Northrop Grumman)

After a nearly half-century quest, the U.S. military today is on the cusp of finally fielding operationally relevant directed-energy weapons. While megawatt-class lasers to shoot down ballistic missiles remain, for now, a distant prospect, today's tactical lasers are potentially useful, cost-effective approaches for countering threats such as low-cost drones and small boats. High-power microwaves open up new avenues for nonkinetic effects, a significant advantage for controlling escalation or limiting collateral damage. Perhaps the most significant benefit to fielding these nascent directed-energy capabilities, however, is that they will start the crucial process of integrating a new technology into operations, with the attendant innovations required in organization, training, concepts of operation and doctrine. Beginning the crucial process of experimentation and concept development to learn how best to employ directed-energy weapons will be critical to ensuring that, as directed-energy technologies continue to mature, DOD is best postured to benefit.

This report by Jason Ellis, a visiting senior fellow at CNAS on leave from Lawrence Livermore National Laboratory, is an important contribution to understanding the promise and prospects of directed-energy weapons. It provides a much-needed guide to this important capability area and offers a candid and objective assessment of the maturity of directed-energy weapons today and what developments may be possible with continued DOD investment. It concludes with recommendations for how DOD should proceed in this area, mindful of past failed promises but driven by the inherent warfighting potential that directed-energy weapons hold. As DOD senior leaders look to better understand the opportunities and feasibility of various candidate technologies for investment, this report provides a valuable resource to help inform their decisions.

EXECUTIVE SUMMARY

By Jason Ellis

The Department of Defense (DOD) must modernize its forces to meet growing anti-access operational challenges within a sharply constrained fiscal environment. It has launched a new Defense Innovation Initiative to identify promising technologies and operational concepts to secure and retain U.S. military advantage. In this context, directed-energy (DE) weapons, including high-energy lasers (HEL), high-power microwaves (HPM) and related radiofrequency technologies, offer the prospect of cost-effective precision attack or enhanced point defense and can provide warfighters with flexible nonkinetic employment options.

But any treatment of the role, relevance and importance of DE weapons to the U.S. defense posture must from the outset deal with the elephant in the room: a history of overpromise and underperformance. DOD's long-standing quest to develop high-energy lasers for ballistic missile defense — in decades past, the well-funded, large-scale and high-profile programs such as the Airborne or Space-Based Lasers — pushed the art-of-the-possible but ultimately failed to deliver viable operational solutions to identified threats. Ironically, today, despite resource levels that are inadequate to fully exploit the potential of directed-energy weapons, there is substantial and growing evidence that laser and microwave weapon systems are finally coming of age for battlefield use.

Indeed, DE weapons have finally demonstrated sufficient technical maturity that they may be integrated into naval, air and ground force structure for various mission applications within the next decade. While more modest in power and capability than previous large-scale DE programs, modern HEL and HPM weapons can help defend ships and bases from some forms of attack; enhance the performance of existing combat identification, self-protection and other systems; and provide novel counterelectronic attack options. As DOD seeks next-generation technologies and operating concepts to offset growing foreign military capabilities, it should seek to close the continuing gap between the warfighting *potential* of directed-energy weapons and their actual *performance* to date. While noteworthy technical progress is evident, there is nothing inevitable about success. And while current developments can lead to a set of battlefield weapons that increase U.S. combat power, they are not yet game-changers.

While noteworthy technical progress is evident, there is nothing inevitable about success

Ultimately, for DE weapons to become serious offset candidates — those technologies that enable U.S. forces to maintain battlefield superiority against any adversary — DOD must become serious about their development. While some technical areas can leverage advances in commercial technologies, there is no commercial market for systems that can effectively counter high-end threats. Therefore, development of substantially more capable DE weapon systems will require that DOD actively shape next-generation capabilities. Their prospective payoff in mission-critical areas warrants focused and sustained senior leader attention.

To realize the capability-enhancing promise of DE weapons in a cost-effective and time-efficient manner, DOD should:

- **Develop, and communicate, a DOD-wide strategic plan.** Defense planning efforts for DE weapons have typically been *prospective* in nature, aligned with future capabilities — should they eventually be developed. Today, even as select weapon systems appear to have reached a point of operational maturity for some missions, their role — and that of subsequent systems — in the defense posture is unclear. DOD needs a game plan: an institutional strategy to develop and field suitable DE weapon systems for the department's highest priorities.
- **Empower, and hold accountable, a DOD champion.** Today's directed-energy developments are largely stovepiped, loosely coordinated under a Communities of Interest framework. Such an approach neither effectively marshals scarce resources toward closing operational capability gaps nor drives the development of operationally relevant weapon systems aligned with DOD's strategic priorities. DOD should build on the existing HEL-Joint Technology Office (HEL-JTO), establishing a joint directed-energy weapon program office to help drive mission-focused programmatic outcomes in a context of time and budget constraints.
- **Resource to effect.** The current fiscal context is clearly the realm of hard choices, but at a ballpark fiscal year 2014 investment of $405.3 million for DE weapons, DOD spends (adjusted for inflation) just 36 percent of what it spent in 2007. If DOD is to field operationally meaningful DE weapons, it should increase spending by two to three times for HEL and by five to 10 times for HPM. With this plus-up, spending would rise to roughly half what DOD spent at the end of the Cold War.
- **Harvest the low-hanging fruit.** DOD has begun to integrate some directed-energy technologies but has not yet fully capitalized on successfully demonstrated high-power radio-frequency weapon developments. At the same time, key solid-state and combined-beam fiber HEL programs will likely be available to transition to the warfighter within the next decade. DOD should push the most promising developments forward, ultimately considering limited-quantity

procurements of those systems that address priority theater warfighting capability gaps.

- **Invest for longer-term success.** DOD conducts research and engineering to create technology surprise for potential adversaries. Yet, current developments largely cater to the lower end of the threat spectrum (for example, unmanned aerial vehicles or small boats). Ultimately, if higher-end threats (for example, high-speed ballistic or cruise missiles) require substantially more capable laser and/or HPM weapon systems, DOD should allocate a greater share of available resources to develop and field effective high-end DE capabilities.
- **Conduct a net assessment and actively monitor foreign developments.** Globalization both erodes longevity in technological superiority and facilitates more rapid development of next-generation technologies. Potential U.S. adversaries benefit from the same underlying technology trends and, in some cases, aggressively seek to counter U.S. military superiority. DOD should increase its coverage of relevant foreign scientific and technical developments, both for early warning and to identify technology breakthroughs and potential opportunities. It should also conduct a net assessment of foreign developments on the U.S. defense posture.
- **Put directed-energy weapons in context.** Directed-energy weapons are not silver bullets, but rather one of a broader set of tools in the warfighter's toolbox. Taken together, the parallel advances in directed energy, cybersecurity and electronic warfare could — if operated as a cohesive system — provide the nation an important, if dynamic, qualitative military edge. While these functional areas are doctrinally linked, they are stovepiped technically and not well-integrated operationally. An enhanced focus on combined directed energy/electronic warfare/cyberexperimentation and wargaming would help DOD appropriately adjust its warfighting concepts, doctrinal approaches, technology development strategies and operational planning.
- **Plan for success.** Finally, although the track record of DE weapons to date leaves much to be desired, DOD should plan for future DE weapon successes. While near-term systems may perform niche operational roles or add only incrementally to U.S. combat power, their more significant contribution will be cultural and organizational in nature — paving the way for the more capable next-generation DE weapons that may carry game-changing effects. Effectively integrating DE weapons into force structure will require adjustments across the doctrinal, organizational, training, logistics, policy and other fronts.

The continuing development and eventual deployment of more capable DE weapons may diminish operational risk, create improved warfighting options and ultimately enable new operational courses of action. Properly executed, leadership and forces will be prepared as new capabilities — effectively shaped by DOD — become available. This is the essence of a competitive and sustaining military advantage and fundamental to the offset strategy sought by defense leadership.

I.
Introduction

I. INTRODUCTION

The electromagnetic spectrum is a critical enabler for modern militaries, at once a source of battlefield advantage and a potential Achilles' heel. In 1956, early in the Cold War and in a context of maturing radar, navigation and communication technologies, Soviet Admiral Sergei Gorshkov boldly declared that "the next war will be won by whichever side best exploits the electromagnetic spectrum."[9] In 2011 — a half-century, several conflicts and myriad electronic warfare measure and countermeasure cycles later — the U.S. chief of naval operations, Admiral Jonathan Greenert, forecast that "in the next two decades, the [electromagnetic] environment may become our most critical warfighting arena." Placing the importance of the electromagnetic spectrum in the context of the revolution in information technologies, he further noted, "control of information – much of it through the EM spectrum – is already growing more important than control of territory in modern warfare."[10] Not surprisingly given its importance, the global electronic warfare market — which includes directed-energy (DE) technologies — continues to grow, from an estimated $7.72 billion in 2010 to roughly $12.15 billion in 2014. Even with downward pressure on defense spending in many countries, analysts anticipate a continued rise to $15.6 billion by 2020, a doubling of the global electronic warfare market in the span of a decade.[11]

The past several decades have seen substantial advances in electronic warfare systems and component technologies that undergird the constituent electronic attack, electronic protection and electronic warfare support missions.[12] Modern electronic warfare systems have benefited from exponential increases in computation and signal-processing capabilities while at the same time achieving ever-smaller size, weight and power configurations.[13] Such advances have been an integral component of maintaining U.S. military technological superiority, enabling and underpinning advanced U.S. surveillance, communication and strike capabilities. Along with a suite of other investments, such as stealth and precision-strike weapons, electronic warfare capabilities have been key components of a high-technology offset strategy that has conferred unmatched operational advantages on U.S. and allied forces for more than four decades. However, as with other critical technology areas, dominance in the electromagnetic spectrum is eroding as the military capabilities of key foreign competitors continue to rise. In September 2014, acting Assistant Secretary of Defense for Research and Engineering Al Shaffer warned that "we have lost the electromagnetic spectrum," expressing concern publicly over the proliferation of high-powered, low-cost and commercially available electronic warfare equipment.[14]

Spurred on by a combination of emerging foreign threats, a defense resource base under siege and an eroding technological edge, Department of Defense (DOD) senior leaders have launched a Defense Innovation Initiative. In August 2014, then-Secretary of Defense Chuck Hagel declared that "we are entering an era where American dominance on the seas, in the skies, and in space — not to mention cyberspace — can no longer be taken for granted."[15] In response, as part of the new initiative, DOD launched a Long-Range Research and Development Planning Program designed to restore American technological advantage in key areas and to cultivate leap-ahead "game-changers."[16] These investments are to enable a "third offset strategy," championed by Deputy Secretary of Defense Robert Work, to renew and sustain America's military primacy.[17]

In this context, directed-energy weapons are among a handful of maturing disruptive or asymmetric technologies that may advance defense priorities in the emerging security landscape.[18] In principle, DE weapons could confer game-changing technological advantages both as a superior defensive capability and as an effective electronic attack option. Yet, the historical record suggests a significant gap between the warfighting *potential* of DE weapons and their *actual* performance to date. While advocates observe real and significant technical progress, skeptics note that true success ultimately requires transitioning relevant technologies from the laboratory into real-world operational settings. Indeed, recent survey data suggests that directed energy is on the menu: Approximately 20 percent of national security specialists polled in February 2014 anticipate that DE weapon technologies will be fully integrated into relevant, stable military systems within the next six to 10 years, while an additional 30 percent agree this will happen within 20 years. But fully half anticipate that this will not materialize for at least 20 years or remain skeptical that DE will ever achieve this objective.[19]

...the historical record suggests a significant gap between the warfighting potential of DE weapons and their actual performance to date.

Certainly, there is no shortage of mission drivers for the development and deployment of directed-energy weapons on the modern battlefield. Both DOD's continuing effort to rebalance its force posture toward the Pacific theater and its continued engagement in South and Southwest Asia underscore the imperative to develop and field capabilities that bolster the U.S. defense posture against regional anti-access and area-denial

DIRECTED ENERGY

Joint doctrine defines directed energy (DE) as an umbrella term covering technologies that produce concentrated electromagnetic energy and atomic or subatomic particles. A DE weapon is a system using DE primarily as a means to incapacitate, damage, disable or destroy enemy equipment, facilities and/or personnel. Directed-energy warfare is military action involving the use of DE weapons, devices and countermeasures to incapacitate, cause direct damage to or destroy adversary equipment, facilities and/or personnel or to determine, exploit, reduce or prevent hostile use of the electromagnetic spectrum through damage, destruction and disruption. It also includes actions taken to protect friendly equipment, facilities and personnel and retain friendly use of the electromagnetic spectrum. With the maturation of DE technology, weaponized DE systems are becoming more prolific and powerful, and a significant subset of the electronic warfare mission area.

Source: Joint Chiefs of Staff, Electronic Warfare, Joint Publication 3-13.1 (February 8, 2012), I-16.

threats. Force protection challenges range from foreign use of unmanned aerial vehicles to small-boat swarms to rocket and missile attack. Capable adversaries can hold U.S. forward operating bases and deployed forces at risk, jeopardizing the nation's ability to project power and potentially undermining escalation-control options. More broadly, foreign development of DE weapons may have implications for the nation's strategic deterrence and homeland defense posture, as increasingly capable directed-energy technologies have the growing potential to hold critical infrastructure or specialized defense capabilities at risk. In each case, there is a developing offense/defense dynamic centered on U.S. and adversary DE weapon developments set within a broader context of global technology diffusion that serves to level the technological playing field.

Ultimately, for DE weapons to become credible near-term (less than five years) to midterm (less than 10) offset candidates — those technologies that enable U.S. forces to maintain battlefield superiority against any adversary — DOD must resolve a chicken-and-egg-style conundrum: whether, and in which specific technology areas, to ramp up necessary investments in order to capitalize on their continuing *promise*. As a starting point, any effort to bolster the DE weapons area must overcome a legacy of exaggerated expectations, technical underperformance and operational irrelevance. Modern DE weapons boast a growing record of progress in key technical areas, however, and are gaining support from an operational community awakening to the promise of DE. Because of that, they could become relevant asymmetric force multipliers for key theater warfighting challenges. It is time to step back, take stock and chart a new course forward for DE weapons in the context of contemporary fiscal constraints, emerging defense priorities and a changing international security landscape.

II.

The Promise of Directed-Energy Weapons

II. THE PROMISE OF DIRECTED-ENERGY WEAPONS

The promise of DE weapons is straightforward. In general, they may:

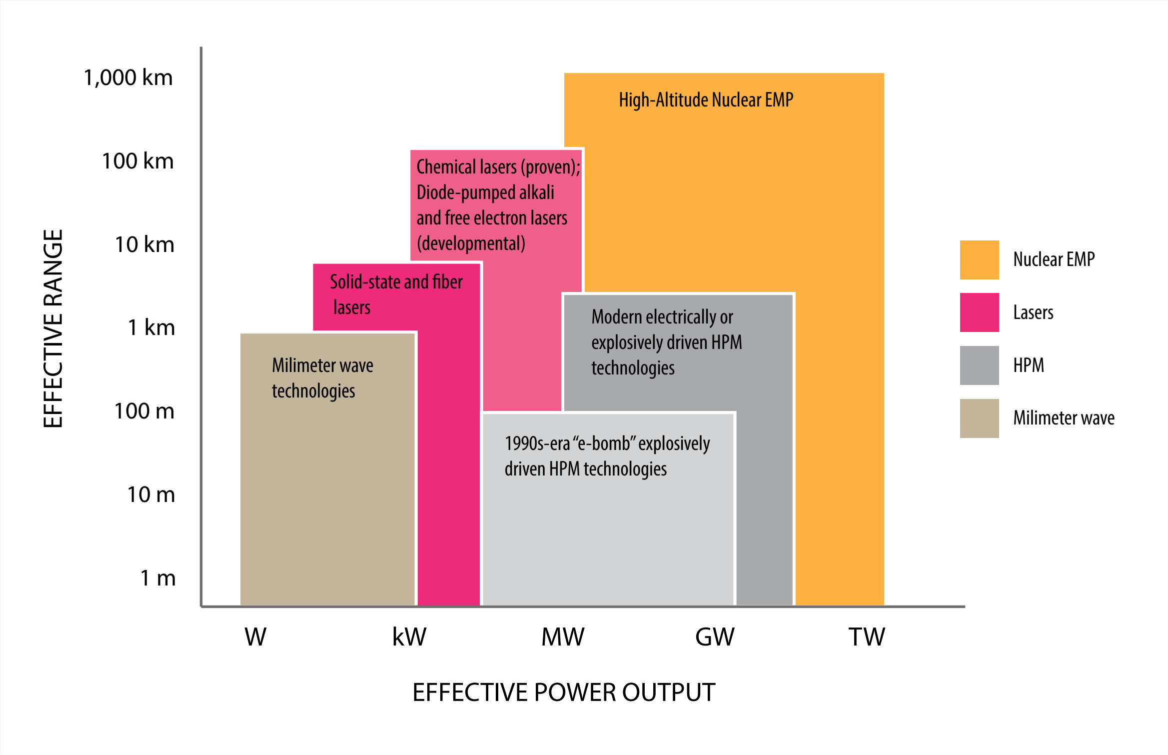
- **Enable defensive and offensive nonkinetic attack options:** Directed-energy systems are precision-effect instruments, a nonkinetic form of joint fires. Modern high-energy laser (HEL) and high-power microwave (HPM) systems are best suited for defensive mission applications, while longer-term aspirations extend to offensive strike missions. The ultimate potential for rapid, accurate and sustained targeting of and strike against fixed and mobile targets at long range is a high-value operational capability. Directed-energy weapons afford the prospect of tailored effects, from lower to higher lethality and from temporary disablement to permanent destruction. Because they may operate at range and may not feature a visible signature, they may be useful for both covert and overt employment.
- **Serve as cost-effective force multipliers:** As with kinetic weapon systems, DE weapons undergo extensive (and potentially costly) developmental and certification processes. Once fielded, however, DE weapons feature a very favorable cost-exchange ratio compared with their kinetic counterparts. While per-system costs vary, a generalized per-shot cost of $1 to $20 is an affordable weapon option. Newer, electric systems can be charged on-station, allowing deep magazines. Because of that, multiple shots per engagement are inexpensive and have a credible probability of effect against susceptible targets. When used as part of a layered defense capacity alongside kinetic weapons, DE weapons can extend aggregate magazine depth and enhance platform survivability.
- **Provide operational flexibility:** The ability to integrate different types of DE weapon systems into a variety of air-, land-, sea- and potentially space-based platforms provides a range of options for the warfighter. Depending on their configuration, they may be forward-deployed or operated from rear areas and may be assigned defensive or offensive missions. Some weapons may be adjusted repeatedly to achieve varied effects within a particular engagement. While some types of DE weapons require favorable weather conditions, others may be capable of all-weather operations. In some cases, DE weapons may have multimission potential — a weapon, but also a potential surveillance, navigation, communication, targeting or other capability.

Consistent with U.S. defense policy objectives, the development and fielding of directed-energy weapons could serve as a powerful force multiplier. Such capabilities could, in principle, bolster the nation's strategic deterrence and homeland defense posture, enhancing missile defense or space control capabilities. For operations in anti-access/area-denial environments, they could strengthen U.S. power projection assets and defend fixed-site installations and/or expeditionary forces from attack. In the Pacific, DE weapons could ultimately bolster air, ground and naval capabilities against operationally challenging raid-density scenarios. With appropriate DE weapon systems, U.S. power projection assets could more reliably operate in "denied" areas, allowing aircraft, forward-deployed naval forces and theater fixed-site installations to stay in the fight longer at reduced operational risk levels. In the Middle East, DE weapons could help enhance force protection against small-boat swarms, unmanned aerial vehicles or rocket, artillery, mortar or missile attack. Properly developed, a decade hence they could provide flexible nonkinetic attack options against adversary integrated air defense systems or command, control and communications nodes, offering potentially valuable escalation-control options. Additionally, they could potentially serve in a robust air-to-ground strike role in support of deployed forces. In each case, DE

DIRECTED ENERGY WEAPONS AT A GLANCE

Many types of DE weapons have been developed or proposed over the past half-century. In the past two decades, HEL, HPM and millimeter wave technologies have proven of greatest interest to the Department of Defense. While the graphic below oversimplifies a complex technical area, it provides a useful framework for how to think about DE weapons.

- High-energy lasers have been the mainstay of DOD's directed-energy weapon developments since the 1960s, affording the prospect of effects ranging from temporary sensor-dazzling through system destruction. Some chemical lasers, designed for strategic missile defense purposes, have demonstrated megawatt-level output. But the large footprint, complex logistics and various technical challenges associated with chemical lasers eventually led to their cancellation. Current developmental megawatt-class systems emphasize free-electron and diode-pumped alkali laser technologies. More recent developments in solid-state and fiber lasers, designed primarily for tactical engagement, feature lower-power systems designed for forward-deployable platforms. Effectively meeting technical challenges including power-scaling, beam quality and thermal management — and packaging for use on appropriate operational platforms — are key to their future prospects.
- Radiofrequency weapons are principally counterelectronic weapons. Starfish Prime and other Cold War-era tests demonstrated the effects of nuclear EMP on electronics; the more modern explosively and electrically driven high-power microwave devices produce non-nuclear EMP effects. High-power microwave weapons have proven capable of gigawatt-class power output that can disrupt or even destroy modern electronics, but at comparatively short range. Radiofrequency weapons can also use millimeter waves for counterpersonnel applications such as crowd control or perimeter security.



Notes: While this is a generalized representation of the effective range and power output of the various laser and radiofrequency weapon types, the actual performance of any system would in practice be system-specific and context-dependent. The nature and form of laser and radiofrequency weapon effects vary considerably. Specific meteorological conditions, atmospheric effects, weapon employment altitude and other variables also affect a system's actual performance.

Sources: Author's estimates, based on available Department of Defense and other public information.[102]

weapons serve as a complement to existing weapon technologies, extending magazine depth on a cost-effective basis, enhancing combat identification, enabling defensive countermeasures against key threats and providing theater commanders the operational flexibility needed to operate effectively against asymmetric adversary capabilities.

The vision is compelling. For these and other reasons, DOD has invested in various directed-energy technologies since the 1960s for both offensive and defensive mission applications. Some, such as low-power lasers, have long been used for communications, navigation, range-finding, target designation and other applications. More challenging have been the development and fielding of high-energy laser, particle beam, high-power microwave, millimeter wave and other weapons-usable radiofrequency technologies. Despite substantial research over the past half-century, directed-energy weapons that are technically credible, operationally usable and acceptable from a policy perspective have proved difficult to realize in practice. Looking forward, select high-power microwave, millimeter wave and high-energy laser systems appear to have the greatest near-term to midterm prospects.[1]

1 Scope note: Consistent with DOD's primary emphasis on countermateriel DE weapon applications, this report emphasizes recent and continuing high-energy laser and high-power microwave developments. Given their counterpersonnel focus, millimeter wave technologies such as the Active Denial System raise a somewhat more nuanced set of policy considerations and are not discussed at length in this report. However, as a mature form of directed-energy weapons developed for military application, they are included in the discussion where appropriate. Other relevant DE technologies, such as low-power lasers, are outside the scope of this report. Similarly, non-DE electric weapon technologies, such as the electromagnetic railgun, are also outside the scope of this report.

III.

Radiofrequency Weapons and Electromagnetic Effects

Photo of 1962 Starfish Prime nuclear EMP event (U.S. Air Force)

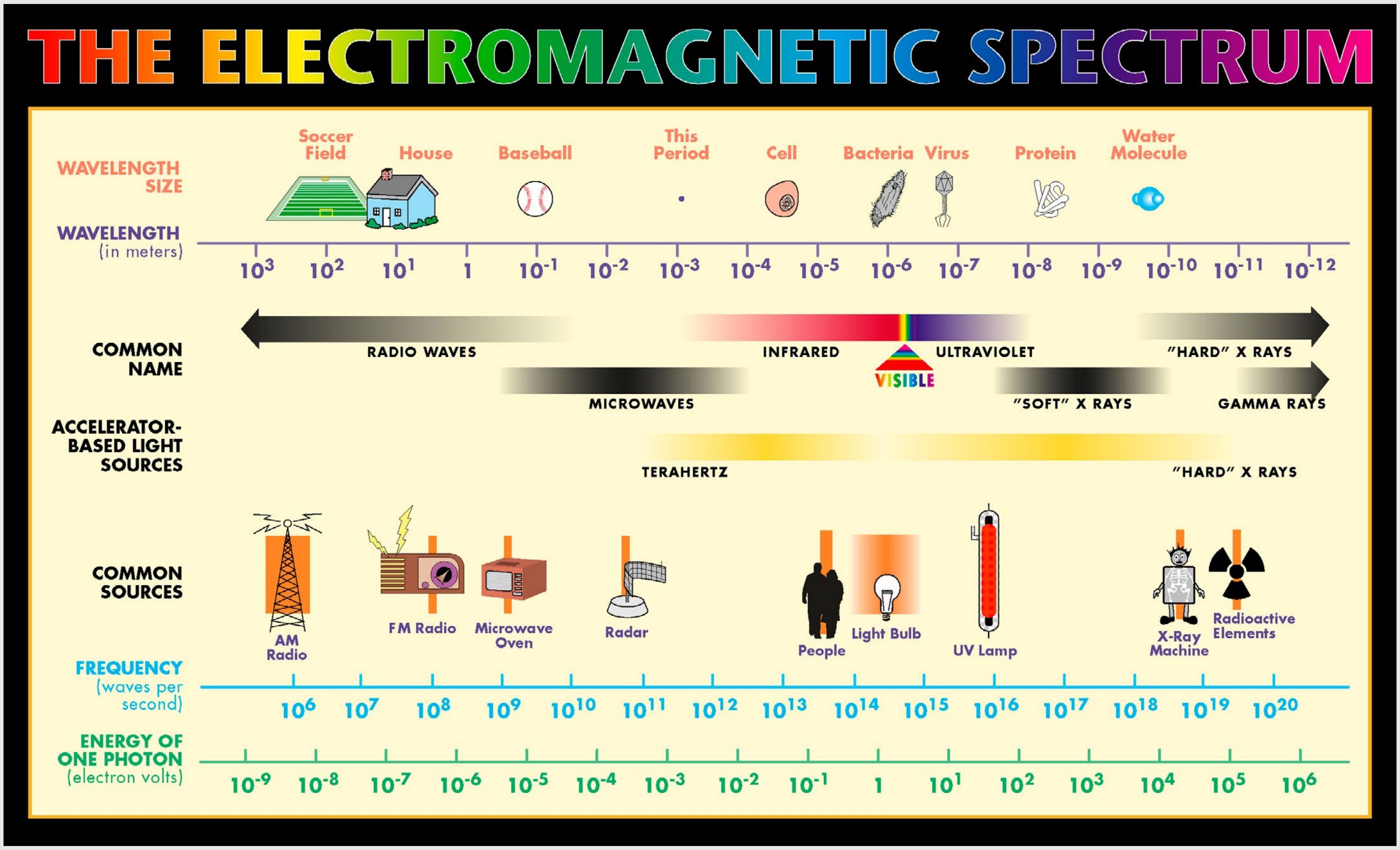
III. RADIOFREQUENCY WEAPONS AND ELECTROMAGNETIC EFFECTS

A Counterelectronics Wake-Up Call

Radiofrequency weapons are "devices that produce and emit electromagnetic energy for the purposes of intentionally disrupting or damaging the targeted electronics."[20] As early as the 1960s, atmospheric nuclear tests highlighted the downrange potential for electromagnetic pulse (EMP) effects on electronic systems. In the July 1962 Starfish Prime test, a 1.4-megaton nuclear device detonated about 400 kilometers above Johnston Island in the Pacific shut off street lights, triggered alarms and otherwise affected the electronic infrastructure of the Hawaiian Islands — more than 1,400 kilometers away — and damaged several satellites in low Earth orbit.[21] In October that year, the Soviet Union conducted Test 184, a series of 300-kiloton detonations at varied altitudes above the test site in Kazakhstan. Their findings were consistent: The nuclear detonations generated adverse effects in downrange electric systems, including a 570-kilometer telephone line, a 1,000-kilometer power cable, transformers, generators and other infrastructure components and subsystems.[22]

In both cases, the prospect of nuclear-induced EMP effects on military and civilian systems opened the door to new, militarily significant electromagnetic attack options and associated protection requirements. By the 1990s, defense analysts openly explored the potential to develop electromagnetic bombs or other "weapons of electrical mass destruction."[23] Some suggested matter-of-factly that "the horse is out of the barn" with respect to radiofrequency weapons and that such weapons "are not a matter of if … but when!"[24] A decade later, the congressionally mandated Commission to Assess the Threat to the

THE ELECTROMAGNETIC SPECTRUM



The electromagnetic spectrum is the range of all types of electromagnetic radiation. Electromagnetic radiation — which can be expressed in terms of energy, wavelength or frequency — can be described in terms of a stream of mass-less particles, called photons, each traveling in a wavelike pattern at the speed of light. Each photon contains a certain amount of energy. The different types of radiation are defined by the amount of energy found in the photons. Radio waves have photons with low energies; microwave photons have a little more energy than radio waves; infrared photons have still more; then visible, ultraviolet, X-rays and, the most energetic of all, gamma rays. High-energy lasers often operate within the visible or infrared portions of the spectrum; high-power microwaves, within the microwave portion of the spectrum.

Source: Adapted from the National Aeronautics and Space Administration, "Switchboard in the Sky," Glenn Research Center.

United States from Electromagnetic Pulse Attack warned that "EMP is one of a small number of threats that has the potential to hold our society seriously at risk and might result in defeat of our military forces."[25]

The Quest for Operationally Relevant Non-Nuclear EMP Systems

While the details of specific defense-related research into high-power microwave and other radiofrequency technologies are not generally available in the public domain, it is possible to trace the broad contours of relevant activities. As a starting point, Naval Surface Warfare Center Dahlgren's Stuart Moran observed that, subsequent to Starfish Prime, "it didn't take long for the military to begin considering ways to generate high-power oscillating electric fields that could be used as a weapon to damage enemy electronics." Among other things, Dahlgren's work included a Special Effects Warhead program that sought to explore the feasibility of "burning out enemy radar and missile systems using single-shot, very-high-peak-power EMPs."[26]

Until the 1980s, however, "damage thresholds were high compared to available microwave output power," according to the Air Force Research Laboratory. The subsequent development of microwave sources with gigawatt-level output, combined with the military's increasing dependency on microelectronics "that were susceptible to upset or burnout at much lower power levels than their predecessors," changed the dynamic and led Air Force researchers to conclude that weapons emitting high-power microwaves "might play important roles on future battlefields."[27] The nation's nuclear weapon laboratories worked closely with service laboratories on high-power microwave system design, including source and component technologies, effects testing, electronics hardening and demonstration programs.[28] By the mid-1990s, the Office of the Secretary of Defense acknowledged that "the technologies are available to build [radiofrequency] devices" and sought more than $283 million for research, development, test and evaluation (RDT&E) activities over fiscal years 1995-2001.[29]

Over the past decade, the scientific community has made noteworthy progress on high-power microwave technologies. These include improvements in microwave sources, antenna design and other long-standing technical limiters to achieving operationally relevant size, weight and power configurations. Collectively, such developments serve to reduce an HPM system's physical footprint, which expands the range of potential employment platforms. They increase a system's power density and extend its effective range, which enhances its operational utility. They also improve a system's ability to operate effectively at different frequencies and, therefore, improve performance against varied target types. Taken together, these improvements significantly enhance the probability of a system's achieving the desired counterelectronic effect.

Counterpersonnel millimeter wave Active Denial System (U.S. Air Force)

ELECTROMAGNETIC PULSE AND EFFECTS "101"

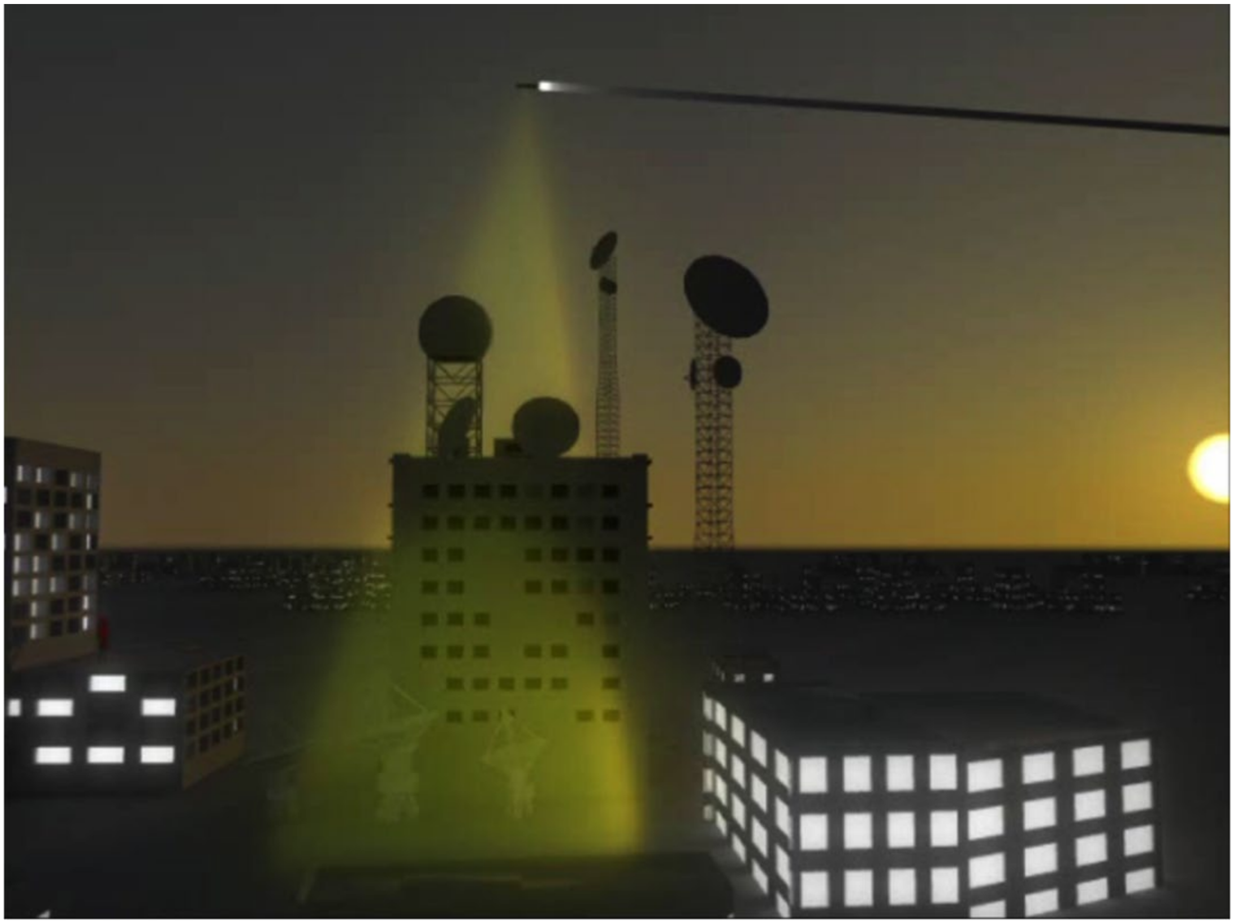
An electromagnetic pulse (EMP) is the burst of electromagnetic radiation created when a nuclear weapon is detonated or when a non-nuclear EMP weapon is used. Naturally occurring solar weather can generate effects similar to aspects of an EMP. EMPs can be high-frequency, similar to a flash of lightning or a spark of static electricity, or low-frequency, similar to an aurora-induced phenomenon. An EMP can spike in less than a nanosecond or can continue longer than 24 hours, depending on its source. The consequences of an EMP range from permanent physical damage to temporary system disruptions and can result in fires, electric shocks to people and equipment and critical service outages. There are four general classes of EMP:

- High-altitude nuclear EMP, which results from a nuclear detonation typically 15 or more miles above the Earth's surface and has the potential for wide geographic effects;
- Source region nuclear EMP, created when a nuclear weapon detonates at lower altitudes within the atmosphere and affecting a more limited geographic area;
- System-generated nuclear EMP, which originates from a nuclear weapon detonation above the atmosphere that sends out damaging X-rays that affect space systems (rather than Earth-based infrastructure); and
- Non-nuclear EMP, generated by explosively driven or electrically driven radiofrequency weapons with effects on electronic components, systems and networks.

The Air Force Research Laboratory characterizes four main types of electronic effects that can be generated by radiofrequency systems:

- Upset is a temporary alteration of the electrical state of one or more nodes in such a way that they no longer function normally. Normal function resumes once a signal is removed. (For example: jamming.)
- Lockup produces comparable upset effects, but an electrical reset is required to regain functionality even after the signal ceases. (For example: computer reboot.)
- Latch-up is a greater form of lockup, in which the electric power to a node is cut off or the node ceases to function. (For example: a blown fuse.)
- Burnout is the physical destruction of a node. (For example: a melted circuit board.)

Sources: Adapted from Brandon Wales, statement before the Subcommittee on Cybersecurity, Infrastructure Protection and Security Technologies, Committee on Homeland Security, U.S. House of Representatives, September 12, 2012; and John A. Brunderman, High Power Radio Frequency Weapons: A Potential Counter to U.S. Stealth and Cruise Missile Technology (Maxwell Air Force Base, AL: Air University, December 1999). See also Philip E. Nielsen, Effects of Directed Energy Weapons (Washington: National Defense University Press, 1994), 206-61.



Counterelectronics High-powered Microwave Advanced Missile Project (U.S. Air Force Research Laboratory)

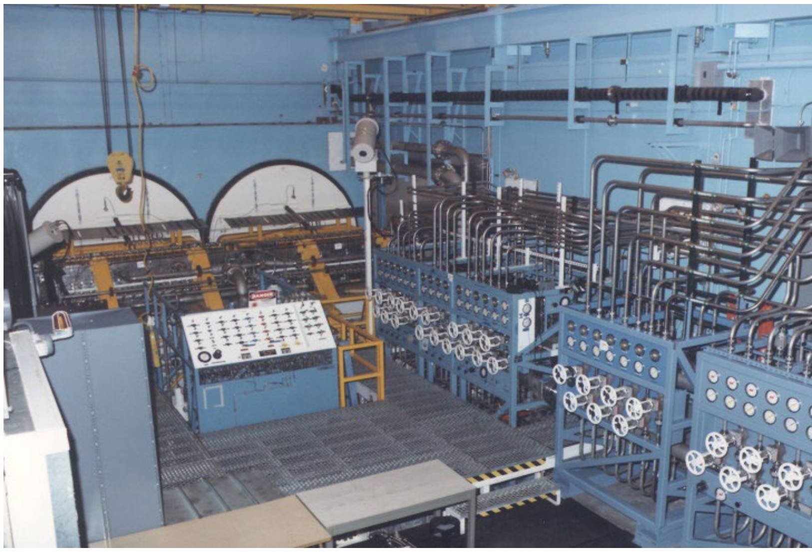
While only select programmatic data are publicly available, at least four programs have seen the light of day. The Active Denial System, a nonlethal millimeter wave counterpersonnel system, was reportedly deployed to Afghanistan in 2010 but withdrawn before use.[30] Two ground-based counterelectronic high-power microwave systems, NIRF and MAXPOWER, were reportedly developed and tested against improvised explosive devices.[31] More recently, the Counter-electronics High-powered Microwave Advanced Missile Project (CHAMP), an air-launched cruise missile with a high-power microwave payload, reportedly successfully engaged a set of electronic targets in an October 2012 test.[32] High-power microwave weapons have been proposed over the past several years for use as a munition, as a nonlethal tool for stopping vehicles or vessels and in other potential counterelectronic mission applications. At the same time, it is clear that both the Chinese and Russian defense communities are actively exploring high-power microwaves and other advanced radiofrequency weapon systems.[33]

IV.
High-Energy Laser Weapons

IV. HIGH-ENERGY LASER WEAPONS

Compared with high-power microwaves and related radiofrequency technologies, high-energy laser systems have historically had a more elevated profile — stemming, in part, from a widespread appreciation for their weapon potential and an early sense of technical progress. Indeed, between 1960 and 1975, the first ruby laser was constructed; a new hydrogen fluoride laser system was demonstrated at the 1-kilowatt level, rising to 100 kilowatts in short order; and a joint Navy–Advanced Research Projects Agency program demonstrated a 250-kilowatt chemical laser system in a laboratory setting.[34] By the early 1980s, the rapid progress demonstrated by these pioneering developments prompted the defense community to actively explore the prospect of both land- and space-based high-energy laser weapons for ballistic missile defense.[35] Over the next two decades, air and missile defense requirements were primary drivers for high-energy laser research and development. Through the Mid-Infrared Advanced Chemical Laser (MIRACL), DOD demonstrated the potential for a megawatt-class chemical laser to engage fast-moving targets (on a crosswise rather than head-on trajectory). After a spike in funding around the end of the Cold War, high-energy laser research and development funding normalized around the fiscal year 2000 level of $475 million — a sum 11 times greater than the $42.4 million planned for high-power microwaves and other directed-energy weapon technologies.[36]

Not surprisingly given the pace of these advancements, the Office of the Secretary of Defense saw the potential for lasers "to emerge as one of the principal weapons technologies underpinning US national security interests" in the 21st century. Defense officials argued in a 2000 report that high-energy lasers "are ready for some of today's most challenging weapons applications, both offensive and defensive," and "offer the potential to maintain an asymmetric technological edge over adversaries for the foreseeable future."[37] The Defense Science Board, which separately reviewed the department's high-energy laser activities in 2001, was similarly upbeat: "High-energy lasers have the potential to change future military operations in dramatic ways." While acknowledging "formidable" scientific, technical and engineering tasks to be overcome, the board concluded that high-energy laser technologies "have matured to the point that a family of applications is feasible over the next two decades, to include systems on aircraft, space vehicles, ships, and ground vehicles."[38] Both groups concluded that DOD should make more resources available for development of improved high-energy laser capabilities, with the aim of developing fieldable laser weapon systems across a wide range of defense missions.



Mid-Infrared Advanced Chemical Laser (U.S. Army)

Early 2000s DOD Investments in High-Energy Lasers Reached for the Stars

Initial ground-based testing suggested the possibility of a fixed-site megawatt-class chemical laser system for terminal missile defense application. However, DOD's two large-scale high-energy laser initiatives, the Airborne Laser and the Space-Based Laser, instead focused on the perceived

Airborne Laser test bed (YAL-1) aircraft (U.S. Missile Defense Agency)

higher-value boost-phase intercept option for missile defense.[39] The Airborne Laser program sought to field a megawatt-class chemical laser aboard a 747 aircraft, with planned forward deployment of a 20- to 40-shot magazine and an initial operational capability by 2010. In addition to the Airborne Laser's primary role as a mobile, rapid-response theater missile defense system, the operational requirements for the program proposed a broader mission set, including:

- Detecting and warning of, and improving countermeasures to, radiofrequency, electro-optical, infrared and acoustic threats to aircraft;
- Neutralizing enemy air defenses;
- Providing nuclear, chemical and biological target detection and improving contamination avoidance; and
- Providing an offensive counterspace capability.[40]

For its part, the Space-Based Laser was conceptualized as a constellation of orbital weapons able to engage and destroy in boost phase missiles launched from any corner of the globe. Early in the development process, it was a longer-term demonstration project whose next major milestone was more than a decade away and whose initial operational capability — if a decision to pursue development was ultimately made — would likely have been post-2020. At an anticipated average annual budget of about $140 million over fiscal years 2000-2005, the Space-Based Laser was a sizable program, but not quite as large as the Airborne Laser's $165 million-per-year average over this time frame.[41] Together, these two programs comprised more than two-thirds of DOD's high-energy laser RDT&E activities.

ILLUSTRATIVE LETHAL EFFECTS FOR HIGH-ENERGY LASER WEAPONS

Estimating the lethality of targets of interest is as much art as science. Variables such as power output and beam quality are among the most significant. As a starting point, the greater the power output the more likely high-energy laser weapons are to achieve lethal effects. But beam quality, a measure of how tightly a beam can be focused, is also critically important. For lasers, the variable M^2 represents the ratio of an actual beam's focused spot size to that of an ideal (Gaussian) beam operating at the same wavelength. Whereas an M^2 of "1" represents a beam with perfect beam quality, an actual, nonperfect beam will have an M^2 value larger than 1. This means that the beam is expanding M^2 times faster than a perfect Gaussian, or, said differently, when the beam is focused it yields a spot diameter M^2 times bigger than that of a perfect Gaussian. Other considerations, such as the susceptibility of specific targets, range to target, atmospheric conditions, potential countermeasures, specific wavelength and additional variables, further complicate probability-of-effect calculations.

While specific estimates will vary, there are sufficient data to suggest the general contours of lethal effects against different types of targets. The table below, published by the Congressional Research Service, illustrates this variability in lethality estimation. Additional empirical testing, together with advances in the state of modeling and simulation tools, should enable improved understanding of weapon effects for high-energy lasers.

SOURCE	BEAM POWER MEASURED IN KILOWATTS (kW) OR MEGAWATTS (MW)				
	~10 kW	TENS OF kW	~100 kW	HUNDREDS OF kW	MW
NAVY BRIEFING (2010)	UAVS				
		Small Boats			
				Missiles (starting at 500 kW)	
SECOND NAVY BRIEFING (2010)		Short-range operations against UAVs, RAM, MANPADS (50 kW - 100 kW; low BQ)		Extended-range operations against UAVs, RAM, MANPADS, ASCMs flying a crossing path (> 100 kW, BQ of ~2)	Operations against supersonic, highly manueverable ASCMs, transonic air-to-surface missiles, and ballistic missiles (>1 MW)
INDUSTRY BRIEFING (2010)		UAVS and small boats (50 kW)	RAM (100+ kW), subsonic ASCMs (300 kW), manned aircraft (500 kW)		Supersonic ASCMs and ballistic missiles
DEFENSE SCIENCE BOARD REPORT (2007)		Surface threats at 1-2 km		Ground-based air and missiles defense, and countering rockets, artillery, and mortars, at 5-10 km[a]	"Battle group defense" at 5-20 km (1-3 MW)
NORTHROP GRUMMAN RESEARCH PAPER (2005)	Soft UAVs at short range	Aircraft and cruise missiles	Soft UAVs at long range	Aircraft and cruise missiles at long range, and artillery rockets (lower hundreds of kW) Artillery shells and terminal defense against very short range ballistic missles (higher 100s of kW)	

Acronymn Key:
UAVs = Unmanned Aerial Vehicles
RAM = Rockets, Artillery, and Mortars
MANPADS = Man-Portable Air Defense System
ASCMs = Anti-Ship Cruise Missiles

Sources: Ronald O'Rourke, Navy Shipboard Lasers for Surface, Air, and Missile Defense: Background and Issues for Congress (Washington, D.C.: Congressional Research Service, August 12, 2010), pp. 34-35; on M^2, see http://en.wikipedia.org/wiki/M_squared.[103]

Meanwhile, DOD Saw Promise in Tactical Chemical Lasers for Battlefield Use

Because missile defense was a central driver, developmental high-energy laser systems sought to achieve megawatt-class output — the power level needed to successfully engage such challenging targets. Other defense missions that addressed "softer" targets could, presumably, be handled with lower-output systems. As such, initiatives such as the High-Energy Laser System-Tactical Army (HELSTAR) suite of programs and the Air Force's Advanced Tactical Laser (ATL) were also in development, though at lower levels of effort. Even though a lower resource priority, lower-power tactical laser technologies made significant technical advancements.

HELSTAR programs, primarily the Army's Tactical High Energy Laser, were designed to advance the Army's battlefield defensive capabilities, with a proximate focus on countering rockets, artillery and mortar rounds. Air Force tactical laser programs sought to achieve a precision-strike capability for air-to-ground engagements. While a lower priority and longer-term developmental effort, the smaller platform sizes envisioned for these mission sets were instrumental both in pushing the envelope with respect to shrinking the footprint of chemical lasers and advancing the state-of-the-art in solid-state laser systems. Electrically powered solid-state lasers largely sidestep the complex logistical challenges associated with chemical lasers, can be packaged for smaller platforms and perhaps as modular payloads that could fit on multiple platform types and can potentially feature reduced system and life-cycle costs. Such a technical evolution would, in principle, make high-energy laser systems more accessible to a broader range of platforms and to a broader set of mission applications.

With the variety of service programs, there was certainly no shortage of ideas for how best to capitalize on such technological advancements. Defense stakeholders sought to deploy these laser systems on tactical aviation and lift assets such as the C-130, V-22, F-22 and CH-47, on ground vehicles such as the Humvee or Stryker and potentially on naval platforms.[42] External observers were similarly optimistic. Northrop Grumman's Richard Dunn observed in 2005, for instance, that "effective laser weapons have already been developed and tested" and that, from a technology development standpoint, "operational laser weapons are right around the proverbial corner."[43]

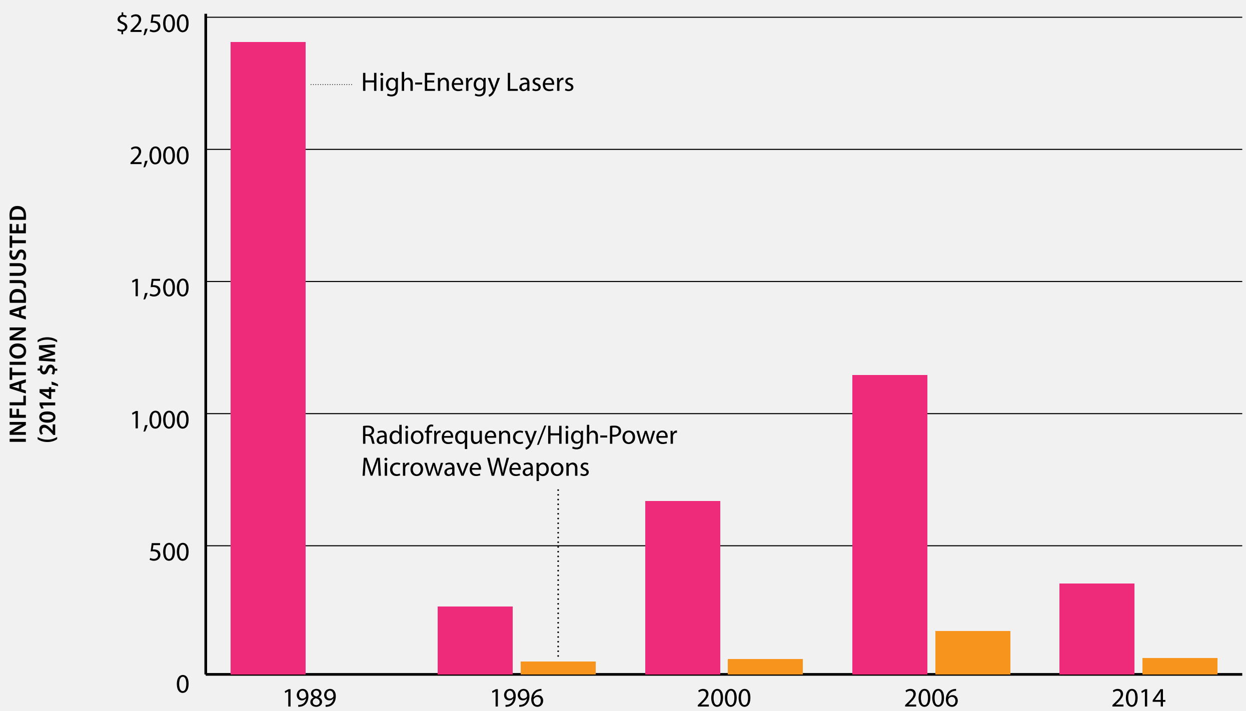
High-Profile Failures Lead to More Sober Assessments

Unfortunately, the various tactical chemical lasers pursued encountered an array of difficult developmental challenges. For their part, DOD's longer-term and higher-risk developmental activities, such as the Airborne and Space-Based Laser programs, encountered significant technical challenges and rising costs. At the same time, DOD leadership placed renewed emphasis on near-term kinetic missile defense options, which reduced enthusiasm for long-pursued high-energy laser developments. Among other things, this led to the termination of DOD's flagship high-energy laser programs: both the Space-Based Laser and,

Laser Weapon System (U.S. Navy)

DOD DIRECTED-ENERGY WEAPON SPENDING OVER TIME

The Department of Defense has pursued directed-energy weapons since the early 1960s, with episodic variations in annual top-line spending. The chart below provides a snapshot of DOD investments in HEL and radiofrequency/HPM technologies at designated time intervals, based on publicly available information. Adjusted for inflation (in 2014 dollars), DOD today spends about 36 percent of what it spent in 2007 — and less than 15 percent of what it spent in 1989 — on high-energy laser weapons. By the same token, DOD spending on lasers over time has substantially exceeded its spending on other DE weapon technologies.



Notes: Author's estimates, based on publicly available Department of Defense information. HEL data estimated for 1989 and 1996. Radiofrequency data unavailable for 1989 and for 1996 represents planned spending. 2000 and 2006 HEL and radiofrequency estimates are derived from Defense Science Board assessments. The 2014 HEL and radiofrequency estimates are derived from fiscal year 2015 RDT&E budget materials. Inflation adjustment calculations courtesy of the U.S. Bureau of Labor Statistics.

Source: Office of the Secretary of Defense [104] later, the Airborne Laser. Such changes appeared to continue an empirical record that, according to informed observers, is grounded in a "history of unfulfilled promises" and "excessive optimism" for HEL weapons that date back to at least the 1970s.[44]

Assessing the state-of-the-art in 2007, the Defense Science Board offered a much more pessimistic review of DOD's directed-energy activities:

> *[While DE] continues to offer promise as a transformational 'game changer' … years of investment have not resulted in any currently operational high energy laser capability [and with this] disappointing lack of progress, there has been a marked decline in interest on the part of operational customers, force providers, and industry.*[45]

The Defense Science Board noted that after many years of development, DOD had yet to field even a single directed-energy weapon system and that fewer programs of record existed in 2007 than when it conducted its review just six years earlier. The board also highlighted a technologist/operator disconnect, observing that "until operational demand generates priorities" for DE weapons development and "until the currently fragmented science and technology projects and programs are focused on moving to research and development programs leading to fielded systems," there is "little reason to expect rapid progress" in fielding either high-energy laser or high-power microwave weapons.[46] The board acknowledged that this assessment stood in marked contrast to its 2001 expectations, as it proved "more difficult than projected" to turn a laser into an effective weapon system.[47]

These more sober assessments of high-energy lasers' potential translated into sharply reduced spending power. In fiscal year 2007, DOD spent $961 million on high-energy lasers.[48] Within four years, however, the amount would fall to $414 million — a cut of almost 57 percent.[49] And by 2014,

High Energy Laser Mobile Demonstrator (U.S. Army)

Concept for ground-based air defense directed energy on the move (Office of Naval Research) it would fall another 17 percent, to about $344 million.

Tactical Solid-State and Combined-Fiber Lasers Are Now Coming of Age

Even as DOD largely downsized its expectations and investments in megawatt-class lasers during that timeframe, the technical state-of-the-art of tactical lasers improved. While some developmental efforts, such as the Missile Defense Agency's (MDA) diode-pumped alkali laser (DPAL) technology or the Navy's free-electron laser (FEL), continue to pursue the traditional megawatt-scale power output objective, most departmental efforts are now focused at lower-power levels of about 10 to 100-plus kilowatts. At such power levels, these tactical lasers would not have sufficient power to destroy ballistic missiles but could prove effective against threats such as drones or small-boat swarms and, potentially, some rocket, artillery and mortar threats.

The type of laser being designed has also shifted. Today's efforts emphasize solid-state and combined-fiber approaches, which are progressing. The Air Force and the Defense Advanced Research Projects Agency (DARPA) are developing a High Energy Liquid Laser Area Defense System (HELLADS) for aircraft self-defense, intended for demonstration aboard a platform such as the B-1 bomber. The Army and Marine Corps continue their respective efforts to develop High Energy Laser Mobile Demonstrator and Ground-Based Air Defense directed-energy on-the-move systems. And the Navy has demonstrated maritime laser defense systems against soft targets, including unmanned aerial vehicles and small boats. As these efforts mature, the operational community is becoming more interested in their capabilities and potential mission applications. David Stoudt, senior director for capabilities and concepts in the Office of the Deputy Undersecretary of the Navy for Policy, captures this broadly renewed optimism for both high-energy laser and high-power microwave technologies: "they have reached the point of being ready for operational testing and evaluation, and in some cases, operational use on the battlefield."[50] Unlike prior optimistic estimates from DOD in the early 2000s, these claims are based not on the unproven promise that DE weapons might someday be available but rather on maturing capabilities that will soon be ready for transition to operational testing and field deployment.

...some DE weapons have finally demonstrated sufficient technical and operational maturity that they may be integrated into naval, air and ground force structure within the next decade.

REAL-WORLD USE OF RADIOFREQUENCY WEAPONS

According to the interagency Technical Support Working Group and the Navy's Directed Energy Warfare Office, radiofrequency weapons are devices that produce and emit electromagnetic energy for the purposes of intentionally disrupting or damaging the targeted electronics. Anything that uses electronics can potentially be affected by radiofrequency weapons, which can damage electronics and/or cause them to malfunction even in ways that compromise built-in, fail-safe mechanisms. Some radiofrequency emitters that are designed for nonhostile applications, such as radars and microwave communication transmitters, can be used as radiofrequency weapons.

The impact of the malfunction depends on what equipment is affected, how and when it is affected and what function it performs. If the affected electronics control critical processes, the impact may be significant, resulting in economic loss, reduced defenses and infrastructure facility downtime. Radiofrequency weapons have in the past been used to defeat security systems, commit robberies, disable police communications, induce fires and disrupt banking computers. For example:

- In the Netherlands, an individual disrupted a local bank's computer network because he was turned down for a loan. He constructed a briefcase-size radiofrequency weapon, which he learned how to build from the Internet.
- In Japan, two yakuza criminals stole from a pachinko machine using a hidden high-energy radiofrequency gun to interfere with the machine's computer and falsely trigger a win.
- In Russia, a criminal robbed a jewelry store by defeating the alarm system with a repetitive radiofrequency generator. Its "manufacture was no more complicated than assembling home microwave ovens."
- Radiofrequency weapons were used in separate incidents against the U.S. Embassy in Moscow to falsely set off alarms and to induce a fire in a sensitive area.

Devices that can be used as radiofrequency weapons have unintentionally caused aircraft crashes and near-crashes, pipeline explosions, large gas spills, computer damage, medical equipment malfunctions, vehicle malfunctions such as severe braking problems, weapons pre-ignition and explosions and public water system malfunctions that nearly caused flooding. For example:

- In 1992, a U.S. Navy ship passing through the Panama Canal left its radar on, damaging nearby computer systems.
- In 1999, a Robinson R44 news helicopter nearly crashed when it flew by a high-frequency broadcast antenna.
- In 2001, there was a mass failure of keyless remote entry devices on thousands of vehicles in the Bremerton, Wash., area, coinciding with the arrival of the USS Carl Vinson.
- In the late 1980s, a large explosion occurred at a 36-inch-diameter natural gas pipeline in the Netherlands. The radiofrequency energy from a naval radar caused the supervisory control and data acquisition (SCADA) system to open and close a large gas flow control valve at the radar scan frequency, resulting in pressure waves that traveled down the pipeline and eventually caused the pipeline to explode.

Source: Adapted from the Technical Support Working Group and Directed Energy Technology Office joint publication, The Threat of Radio Frequency Weapons to Critical Infrastructure Facilities, August 2005.

V.

Implications of a Changing Directed-Energy Weapons Posture

V. IMPLICATIONS OF A CHANGING DIRECTED-ENERGY WEAPONS POSTURE

In a perfect world, directed-energy weapons would:

- Be scalable, offering both high and low power output potential;
- Demonstrate the ability to operate effectively at a wide range of frequencies;
- Be compact and highly efficient, to minimize power, cooling and other system component requirements;
- Feature modular designs, able to fit within and operate from a variety of platforms;
- Require little training or special handling;
- Have a light logistics tail and consumables footprint; and
- Be available when needed, capable of rapid and sustained operation.

While certain high-power microwave and high-energy laser components and enabling technologies may meet many of these criteria, integrated systems that meet *all* of these criteria remain in the realm of science fiction. With a perceived long history of overpromise and underdelivery, it is important to understand what emergent DE weapons technologies can — and cannot — provide in the near-term to midterm. A long time in the making, some DE weapons have finally demonstrated sufficient technical and operational maturity that they may be integrated into naval, air and ground force structure within the next decade. While more modest in power output than past high-end developmental systems, proven DE weapon developments enable fielding of a new generation of combat capabilities primarily suited to defensive mission applications against lower-end threats.

Modern High-Power Microwave Systems Enable Short-Range Non-Nuclear EMP Strike and Defensive Options

More than a half-century ago, Starfish Prime galvanized attention on nuclear-generated EMP effects on electronic systems. More recently, the EMP Commission focused primarily on the threat posed by a high-altitude nuclear detonation above U.S. territory. But increasingly capable non-nuclear high-power microwave systems pose a growing threat to electronic systems and to defense and homeland critical infrastructure, as a globalizing marketplace portends a "leveling of the technological playing field."[51]

> *Western civilization is not at risk of collapse as a result of a disgruntled subnational actor with $400 to spend and access to Fry's Electronics or Best Buy.*

At the same time, society's growing dependence on electronics and the interdependence of critical infrastructure combine to create increasing vulnerabilities to electronic attack and open the prospect of cascading failures that transcend single-point vulnerabilities.[52] For *IEEE Spectrum* contributing editor Robert Charette, the "risk will simply build cumulatively over time, as ever increasing amounts of electromagnetically soft digital equipment is embedded into an ever more interconnected and internally interdependent digital information infrastructure."[53] And while EMP hardening options exist — adding, by some estimates, on the order of 1 to 3 percent to the system cost when included in initial designs — they have not typically been included in either defense or critical infrastructure system or component specifications to date.[54] In this respect, DOD Instruction 3222.03, which articulated in August 2014 the department's policy to control electromagnetic effects as an acquisition life-cycle design criterion, is a welcome vulnerability-reducing step for future military platforms, systems, subsystems and equipment.[55]

To be sure, this widespread vulnerability is not limited to the United States or to the nation's defense sector. Indeed, as the accompanying text box illustrates, the non-nuclear EMP-related events the United States has experienced to date have had more to do with local law enforcement or homeland security equities. But the record thus far falls more in the realm of small-scale experimentation and hobby science than of militarily relevant weapon capabilities designed to conduct a serious electronic attack. Certainly, the popular literature is replete with fears of an "e-bomb" accessible to terrorists or other subnational actors. For *Discover Magazine* production editor Michael Abrams, "crude" forms of HPM technology are readily available, while "anyone with a technical bent could probably also build a crude e-bomb in their garage."[56] In *Popular Mechanics* science editor Jim Wilson's assessment, for about $400 terrorists could build an e-bomb that "could throw civilization back 200 years," and in the "age of third-world sponsored terrorism, the E-bomb is the great equalizer."[57] In turn, former defense policy analyst Michael Maloof identifies multiple, publicly available Internet sources that claim step-by-step methods to build a simple EMP generator or other radiofrequency weapon.[58]

While non-nuclear EMP-generating weapons are possible and would deliver localized disruptive effects, some of these claims are assuredly overblown.[59] Even as high-power microwave weapons are capable of all-weather operations, their effective range can be limited by physical principles (for example, those affecting beam attenuation), their effectiveness can potentially be mitigated by shielding or other countermeasures, and limited test data on modern systems suggests potentially significant error bars in weapon lethality. Additionally, as former Defense Nuclear Agency Deputy Director George Ullrich notes, the popular literature frequently conflates two very dissimilar threat scenarios — that of nuclear-generated high-altitude EMP and that of more localized non-nuclear EMP — leading at times to "absurdly exaggerated claims regarding the aftermath of an E-bomb attack against modern electronics-based infrastructure."[60]

But there is no escaping the march of technology.

But there is no escaping the march of technology. Because the technical underpinnings of non-nuclear EMP devices have been around for several decades, in Ullrich's view "it should be no surprise that the components needed to fabricate such devices are all commercially available" or that "pulse power technology and [HPM] sources have matured to the point where practical electrically driven EMP devices and explosively driven E-bombs are within reach."[61] Indeed, even as governments continue to advance relevant scientific and technical capabilities, private companies such as e2v and Diehl already offer radiofrequency devices for law enforcement and other applications, including vehicle-stopping, and will most likely improve and expand their product offerings over time. Thus, it is possible for subnational actors to construct or purchase a commercial HPM device capable of limited electromagnetic effects. But here's the bottom line: Western civilization is not at risk of collapse as a result of a disgruntled subnational actor with $400 to spend and access to Fry's Electronics or Best Buy.

For the military, emergent high-power microwave technologies capable of multigigawatt power densities could provide novel force protection and precision-strike options. While defense scientists have in the past considered how to weaponize HPM in the form factor of, for example, a general purpose bomb, newer-generation capabilities such as the Air Force's CHAMP provide improved, stand-off strike capabilities. At the same time, the technology behind HPM has evolved. Older, explosively driven HPM technologies were traditionally capable of single-pulse and fixed-waveform output with potentially low probability of effect against some targets. More recent HPM devices are electrically driven, yielding high-repetition rate, more agile waveforms and greater power output. This has the potential to both meaningfully reduce device size and significantly enhance weapon

REPRESENTATIVE HIGH-ENERGY LASER SYSTEMS

The term "laser" stands for "light amplification by stimulated emission of radiation." Light, consisting of tiny packets of energy called photons, is a type of electromagnetic radiation. The laser device produces high-energy light at a particular wavelength or small set of wavelengths. The amount of energy is what determines the wavelength; lasers are usually infrared (1mm to 750nm) or visible light (750-400nm).

Lasers emit a narrow beam of light, which will diffract, or spread, gradually over time. The degree of diffraction of any electromagnetic radiation beam is based on the wavelength and aperture size. Because of their smaller wavelength, for the same aperture size, lasers diffract 10,000 times less than microwaves. This allows the beam to reach farther ranges while maintaining a small spot size of concentrated energy on the target.

Generally, a laser weapon is any laser used against the enemy with more than 50kW to megawatts of power — much greater power than commercial lasers. Different device technologies will produce widely different power levels and beam quality.

Building an HEL weapon system requires more than simply providing a laser device with a specific power level. It also requires a means for getting the laser power out of a beam director toward the target in such a way that the laser beam can deliver a lethal fluence on the target. (Fluence is the energy per unit area deposited by the laser on the target.) The laser energy must couple efficiently to the target, and it must exceed some failure threshold that is both rate-dependent and target-specific. Elements typically included in an HEL weapon system include the laser device, a "local loop" or beam transfer system, a "target loop" which ensures that the beam delivers its punch to the target, a propagation stage, the target coupling and the lethality mechanism associated with the laser.

Over the past half-century, the Department of Defense has invested in a broad array of high-energy laser weapon technologies designed for varied mission applications. While there are many types of lasers, those of greatest interest to DOD over the past several years include:

- Chemical lasers, such as the Airborne Laser or Mid-Infrared Advanced Chemical Laser, have demonstrated the ability to produce megawatt-class power output. All of the military services had developmental programs in the early 2000s, with an eye toward air-to-air, air-to-ground, missile defense and other applications. However, they faced substantial challenges in reducing their footprint to fit on smaller platforms, in managing the complex logistics and handling considerations associated with hazardous materials, and in addressing a rising cost profile raised by unforeseen technical challenges. The full suite of chemical laser programs pursued in the 1990s-2000s has been canceled.

- Solid-state lasers are electrically driven. Their power output is lower than that of chemical lasers, but they largely sidestep the complex logistics and handling of their chemical counterparts. Solid-state systems are typically modular and therefore scalable. The combined-fiber systems of interest to DOD seek to link several lasers together to achieve power densities exceeding 100kW for battlefield use. It is not yet clear how far such technologies can scale in operationally relevant size, weight and power configurations, but it appears that low-hundreds of kilowatts may prove feasible. While not yet proven, some solid-state systems, such as the diode-pumped alkali laser, may ultimately be able to achieve megawatt-class levels on tactical platforms.
- Free-electron lasers seek to adapt high-energy particle accelerators for ship/fleet-defense purposes. While not yet proven, this type of laser may ultimately be able to achieve megawatt-class levels.

ILLUSTRATIVE MISSION	EFFECT DESIRED	OUTPUT NEEDED (kW)	REPRESENTATIVE SYSTEM	LASER TYPE	KEY CONSIDERATIONS
COUNTER-VEHICLE (UAVS, SMALL BOATS)	Disablement/ destruction	10s	Laser Weapon System (Navy)	Solid-state/fiber	Developmental (seeking 100kW+)
COUNTER-ROCKETS, WARTILLERY, MORTARS	Destruction	10s - Low 100s	HELLADS (DARPA/ Air Force)	Solid-state	Developmental (seeking 150kW)
			HELSTAR (Army)	Chemical	Program canceled
AIRCRAFT SELF-PROTECTION	Disablement	1 - 10s	DIRCM (Air Force)	Solid-state	Acquisition program
AIR-TO-AIR ENGAGEMENT	Destruction	Low/Mid-100s	Tactical HEL Fighter (Air Force)	Chemical	Program canceled
AIR-TO-GROUND PRECISION STRIKE	Destruction	Low/Mid-100s	ATL (Joint)	Chemical	Program canceled
			Excalibur (DARPA)	Solid-state/fiber	Developmental (seeking 100kW)
AIR AND MISSILE DEFENSE	Destruction	Mid-100s - 1000s	Airborne Laser (MDA/Air Force	Chemical	Program canceled
			DPAL (MDA)	Solid-state	Developmental (seeking 1MW+)
			FEL (Navy)	Free-electron	Developmental (seeking 1MW+)
SPACE CONTROL	Disablement/ destruction	Varied	Ground-Based Laser (Air Force)	Chemical	Program canceled

Sources: Adapted from Melissa Olson, "History of Laser Weapon Research," Leading Edge, 7 no. 4 (n.d.), 26-35; and Office of the Secretary of Defense, Report of the High Energy Laser Executive Review Panel: Department of Defense Laser Master Plan, DOD/S&T/00-001 (March 24, 2000). Table compiled by the author, based on publicly available data. [105]

lethality against an expanded array of targets. Such developments set the stage for non-nuclear EMP-generating technologies to be fielded for battlefield use. While they do not afford the long-range effects associated with Starfish Prime, they represent technical advances that substantially improve on the systems demonstrated thus far and can put operationally relevant HPM capabilities in the hands of the warfighter.

For anti-access/area-denial operations, the ability to penetrate adversary airspace and deliver tailored nonkinetic effects against integrated air defense, command and control or other electronic systems is a high-value capability. Once fielded, such capabilities will become integral to the military's ability to project power in contested operational environments. In some situations, they also could be used for escalation control, giving commanders a nonkinetic attack option. In some respects, HPM's offensive potential against critical adversary systems could invert the anti-access problem. Properly integrated into a combined, synergistic kinetic/nonkinetic theater warfighting concept, they could become a useful arrow in the quiver of a U.S.-styled version of China's "Assassin's Mace" concept.[62] At the same time, the prospective utility of high-power microwave systems for point-defense purposes underscores their importance in a range of tactical scenarios.

Emergent High-Energy Laser Weapons Enable Limited Defensive Options

The emerging set of technically mature high-energy laser weapons is best suited for defensive applications. At higher power levels they could also become viable strike weapons. The solid-state and combined-fiber laser systems of growing interest to department stakeholders are more limited in power output than past chemical lasers but potentially more usable for point defense of expeditionary or mobile ground, naval and air assets against rockets, artillery, mortars or soft targets such as small boats or unmanned aerial vehicles. Indeed, among the more striking implications of the evolution of high-energy laser weapon technologies is the stark redefinition of weapon development objectives over the past 10 to 15 years. While defense leadership placed great emphasis on high-energy laser weapons for strategic missile defense from the 1980s into the early 2000s, megawatt-class systems are today back-burner items. Meeting the technically daunting demands of this mission set proved costly and, although they made significant technical progress, the technologies available at the time generally proved insufficient to the task. Achieving megawatt-scale output remains an aspirational goal, but the reduced national effort on the technologies that could most likely achieve this objective — chemical, diode-pumped alkali and free-electron lasers — underscores both a changed programmatic focus and shifting mission priorities. It may also foreshadow the difficulty of undertaking and sustaining longer-term and higher-risk developments during a time of sharply constrained resources.

At the same time, DOD's weapon development efforts associated with kilowatt-class lasers have grown in relative importance. The prospective attributes of speed, range, flexibility and precision have made DE weapons one of the five strategic technology areas the Air Force intends to pursue over the next three decades.[63] In particular, research activities prioritize laser systems designed to operate at roughly 10 to 150 kilowatts, primarily for aircraft self-defense. The Navy envisions that electromagnetic maneuver warfare will become a "primary means" of warfighting in 2025.[64] Although the Navy seeks eventually to develop megawatt-class systems such as the free-electron laser for ballistic missile and carrier battle-group defense, contemporary efforts emphasize more mature, lower-power systems. The Laser Weapon System, an approximately 33-kilowatt fiber laser system, was demonstrated aboard the *USS Ponce* in November 2014, and the Navy is moving forward with follow-on technology maturation efforts. This prototype and its solid-state Maritime Laser Demonstrator counterpart are designed primarily for counter-unmanned aerial vehicle, countermaritime vessel and related combat identification and force protection applications.[65] For Congressional Research Service analyst Ron O'Rourke, equipping Navy surface ships with high-energy lasers could *ultimately* bring about a "technological shift for the Navy — a 'game changer' — comparable to the advent of shipboard missiles in the 1950s."[66]

With respect to ground force applications, the Army sees the potential for directed-energy weapons to disable, damage or destroy an enemy's equipment or capability.[67] Despite Assistant Secretary for Acquisition, Logistics and Technology Heidi Shyu's concern over a general Army modernization "death spiral," Army high-energy laser developmental efforts continue and its scientific community remains engaged in such areas as electromagnetics and antennas.[68] Longer-term high-energy laser development options for both the Army and Marine Corps are designed to enhance counterrocket, artillery and mortar defense — a defensive capability that could be useful against adversary salvo attacks for forward-deployed or maneuver forces.[69]

Meanwhile, research on the necessary steps to ultimately achieve megawatt-class lasers continues, albeit at a reduced level. Defense organizations including DARPA and the Missile Defense Agency continue to advance work on beam-combined fiber lasers and highly efficient and scalable diode-pumped alkali laser technologies.[70] Recent research by Lincoln Laboratory and Lawrence Livermore National Laboratory suggests that it may be possible to significantly increase the power output of fiber laser systems, opening the eventual prospect of multihundred-kilowatt systems.[71] In turn, the continuing development of high-power laser diodes enables, in former Livermore Deputy Associate Director Bill Krupke's view, "a significant increase in the efficiency, power, and compactness of bulk solid-state lasers" and carries with it the longer-term prospect of megawatt-class potential.[72]

At the same time, it is important to underscore the limitations of the current set of technology developments. Laser weapons require line-of-sight to the target (or more sophisticated relay mirror concepts). Their effectiveness at range can be mitigated by beam-propagation and optical tracking challenges. Their operation can be challenged by thermal management and handling considerations. And their lethality can be compromised by environmental factors and countermeasures. In their current form, the high-energy laser weapons under development are primarily defensive in nature. With some possible exceptions, they are not yet capable of the power output required to serve as viable attack options that support the air-to-air, surface-to-surface or air-to-surface engagements advocates have proposed.[73] Nor are they positioned to effectively counter some of the most dangerous emerging threats to deployed forces, such as ballistic missiles or supersonic cruise missiles. As the accompanying text box suggests, engaging such fast-moving targets requires both a high-quality beam and a significant increase in power output. Should solid-state or combined-fiber systems eventually achieve multihundred-kilowatt power densities, they may provide some capability in this area. Additional susceptibility testing will be required against representative targets of interest to determine more precisely the power levels required to achieve the desired effects. Ultimately, a more effective solution would be to advance development of megawatt-class systems for the challenging anti-ballistic and supersonic cruise missile missions.

Even with successful demonstration activities or unanticipated technological breakthroughs, there are no programs of record established (as of fiscal year 2014) to transition the DE weapons being developed. Even if there were, the power-scaling potential of solid-state and fiber lasers to rise from, say, the 33-kilowatt Laser Weapon System or the 105-kilowatt Maritime Laser Demonstrator to a more operationally significant 300-kilowatt (or higher) system is not yet clear. Certainly, the Navy has signaled that success with both the USS Ponce demonstration and the accompanying multiyear Solid-State Laser Technology Maturation development effort "will pave the way for a future acquisition program of record so we can provide this capability across the fleet."[74] The current fiscal environment will make funding a new DE weapon program challenging, however.[75] This suggests that even with technology success, the department is not well-positioned to capitalize expeditiously on such successes, to accelerate their further development or to transition rapidly to an acquisition program.

...today's departmentwide inventory is an eccentric amalgamation of projects rather than a cohesive program.

On balance, the near-term shift toward kilowatt-scale systems demonstrated in relevant operational environments is a net positive for the development of DE weapons. But anticipated technology development timelines at current resource thresholds suggest it is not likely to lead to near-term operationally deployed weapon systems. Many of the envisioned missions for these current-generation systems can be serviced by available kinetic alternatives; in most cases they do not, today, offer a unique warfighting capability. Rather, once fielded these prototype DE weapons will serve as force multipliers, adding magazine depth, extending engagement range and/or enhancing combat identification capabilities. By the same token, if their added value is not sufficient to justify the development and integration cost, their successful demonstrations may not lead to formal acquisition programs. Moreover, current developmental systems are not yet ready for more robust (multihundred-kilowatt) missions and thus carry the inherent risk of exaggerated performance expectations. Recent experiences with the millimeter wave Active Denial System (which has not been successfully fielded) and the laser-based Directed Infrared Countermeasure System (which has been successfully fielded) provide countervailing examples of the prospects for technology adoption. At minimum, they highlight the significant potential sociological, policy or operational barriers that must be overcome for nascent DE weapon technologies to come fully of age.

Still, these lower-output weapons appear well-suited to their downsized mission applications. Their adoption may help bridge a long-standing divide between the scientific and operational communities with respect to DE weapon requirements. Lower-output weapons may be able to capitalize on noteworthy technology improvements in areas such as beam control and tracking. Perhaps most importantly, they could provide a quick "win" for operational DE weapons. If so, they could usher in a modern-day renaissance for DE weapon technologies more broadly.

VI.

Findings and Recommendations

VI. FINDINGS AND RECOMMENDATIONS

Two decades ago, the Air Force Scientific Advisory Board forecast that both high-power microwave and high-energy laser weapons would become ubiquitous on future airborne platforms by the present era.[76] Since then, progress has been uneven. While DOD's development of directed-energy weapons may have survived a near-death experience after the cancellation of previous large-scale and high-profile programs of record, today's departmentwide inventory is an eccentric amalgamation of *projects* rather than a cohesive *program*.

Ultimately, for DE weapons to become serious candidates for the department's new offset strategy, DOD must become serious about their development. DOD has made substantial technical advancements in both high-power microwaves and high-energy lasers over the past several years, and the state-of-the-art would arguably permit accelerated development options in key areas. But on their current course, existing and anticipated developmental activities for the full range of enabling and component technologies will not likely lead to fielded, operationally relevant DE weapon systems for the next several years. Although the long-standing promise of directed-energy weapons remains, there is nothing inevitable about success; and while current developments can lead to a set of battlefield weapons that are accretive to U.S. combat power, they are not yet game-changers. While it is possible to build on current developments, it is time for a midcourse correction if DE weapon systems are to live up to their promise as credible near-term to midterm force multipliers. DOD senior leadership should advance DE weapons development along a cohesive, mutually reinforcing eight-part approach. Each item is useful in its own right, but they together provide the basis for a qualitatively new approach to modern DE weapons development.

1. DEVELOP, AND COMMUNICATE, A DOD-WIDE STRATEGIC PLAN FOR DIRECTED-ENERGY WEAPONS.

For years, the defense and scientific communities have considered a range of potential offensive and defensive roles for directed-energy weapon systems. But they have typically been *prospective* in nature, aligned with future capabilities — should they eventually be developed. Today, even as select high-energy laser, high-power microwave and millimeter wave technologies appear to have reached a point of operational maturity, the role of DE weapons in the current defense posture is unclear. Nor is their envisioned future role in the longer term any more clear when, presumably, the state-of-the-art has advanced further. This general lack of strategic vision has some exceptions, to be sure. For example, the Navy recently developed — but has not yet publicly released — a DE road map, and both the Air Force and Army Research Laboratories periodically showcase their multiyear research intent. But if weapons are to transition effectively to the field, and if approaches such as the Joint Concept for Access and Maneuver in the Global Commons are inherently joint, then DOD must develop and promulgate cross-service approaches to DE weapons development. DOD must also work to more effectively ensure that DE developments address regional combatant command capability gaps in support of DOD mission priorities.

...the DE weapons area is a technological orphan — influenced by many and owned by none.

In this respect, the High Energy Laser Master Plan developed by the department in 2000 may provide a reasonable starting point for action. That plan, required by statute, served both as a mechanism to align expectations across the services and the Office of the Secretary of Defense and as a planning catalyst for out-year development efforts. Much has changed in the 15 years since that document was established. It is time for a fresh look.[77] The new plan should include the full range of DE weapon technologies and provide for development of appropriate joint DE weapon development strategies, service concepts of operation and identified courses of action for the relevant theater plans.

2. EMPOWER, AND HOLD ACCOUNTABLE, A DOD CHAMPION FOR DE WEAPONS.

The secretary of defense should identify a champion within DOD for directed-energy weapons. By default, since most DE weapon activities were developmental in nature, the director of defense research and engineering (DDR&E) played that role in the past. In that informal role, the DDR&E (now the assistant secretary of defense for research and engineering) oversaw, resourced or otherwise worked closely with the technical agencies most involved in DE weapon developments. The department's 2007 research and engineering strategy, for instance, noted DE capability gaps, research priorities and mission applications.[78]

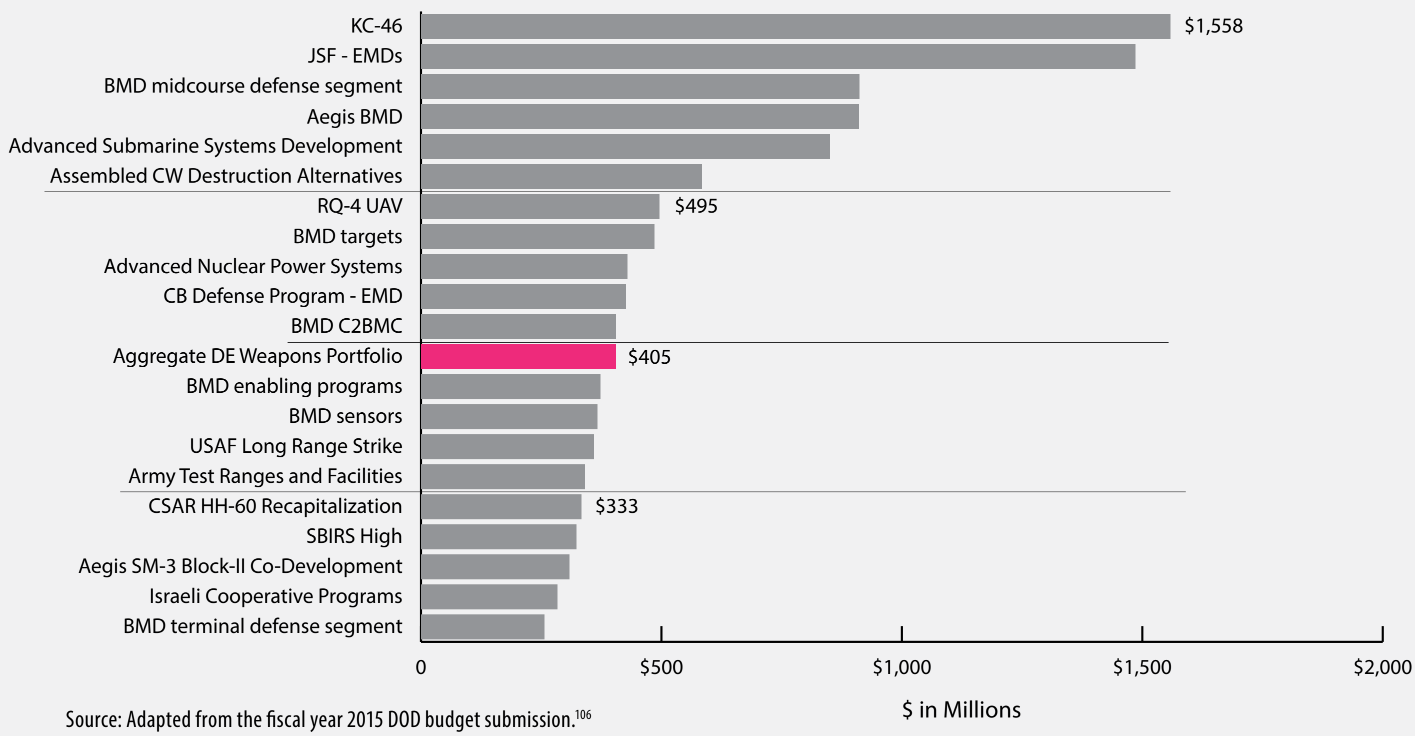
Today, the department has lost a cohesive focus in the DE area. DOD's 2014 research and engineering strategy does not emphasize directed-energy weapons, although it highlights the need for both electronic warfare and long-range strike capabilities.[79] Organizations such as the High Energy Laser-Joint Technology Office (HEL-JTO) continue to work across common service technical needs, but DOD has no joint high-power microwave-focused counterpart. And while there is clear benefit in joint *technology* developments, a joint *program* office could potentially play a stronger role in driving focused programmatic outcomes in the context of identified time and budget constraints. Moreover, while the Navy has centralized responsibility in a single office to steward its DE programs, other services do not appear to have as clear a center of gravity. Rather, the department's present laissez-faire developmental approach is shepherded by confederated "communities of interest" (COIs) organized by the Office of the Secretary of Defense.

The old adage remains true in the DE weapons area: no bucks, no Buck Rogers.

According to the Office of the Assistant Secretary of Defense for Research and Engineering, COIs serve as a "forum" for coordinating science and technology strategies across the department.[80] There is no dedicated COI for DE weapon technologies. Rather, relevant DE technologies cut across several of the 17 current COIs: the weapons technology and electronic warfare COIs, certainly, but also those addressing advanced electronics; sensors and processing; materials and processes; space; ground, air and sea platforms; and potentially others.[81] Yet, while technical collaboration can be beneficial — particularly in a cost-constrained environment — no one, *by design*, is driving the train. And while the COIs seek to "encourage" multiagency coordination and collaboration in cross-cutting technology focus areas, they focus on DOD organizations. While understandable, it does not in practice support a broader focus on the relevant scientific and technical capabilities of other federal agencies and research centers, which further constrains their collaboration potential. As a result, the current context may enable a thousand programmatic flowers to bloom within DOD, but it neither effectively marshals scarce resources toward closing operational capability gaps nor

DOD DIRECTED-ENERGY WEAPONS RDT&E PORTFOLIO COMPARED WITH SELECT FY14 RDT&E PROGRAMS

In fiscal year 2014, DOD spent about $63.1 billion on research, development, test and evaluation activities. Of this, it spent about $405.3 million — six-tenths of 1 percent — on the directed-energy weapons portfolio. In comparison, DOD spent more than three times this amount for RDT&E on major defense acquisition programs such as the Joint Strike Fighter and the KC-46 tanker; more than twice as much on Aegis; more on platforms such as the RQ-4 unmanned aerial vehicle; more on ballistic missile defense targets, command and control, and midcourse defense; and more in areas such as advanced nuclear power systems, submarine systems development and chemical weapons destruction. Arguably, this reflects both the department's near-term acquisition priorities and its near-term expectations for developmental directed-energy weapon systems.



Source: Adapted from the fiscal year 2015 DOD budget submission.[106]

drives the development of operationally relevant DE weapon systems aligned with the department's needs. Indeed, under the current COI structure, the DE weapons area is a technological orphan — influenced by many and owned by none.

3. RESOURCE TO EFFECT.

The old adage remains true in the DE weapons area: no bucks, no Buck Rogers. The current fiscal context is clearly the realm of hard choices, but resources will be required if operationally relevant DE weapons are to fully come of age. This is not surprising; the ballpark $405.3 million DOD spent in fiscal year 2014 is, when scaled for inflation, just 36 percent of what it spent in fiscal year 2007.[82] This finding also echoes the Defense Science Board's recent finding that, to maintain a competitive electronic warfare posture in a contested electromagnetic environment, the department should target an additional $2 billion per year in electronic warfare investments.[83] (For fiscal year 2015, DOD requested approximately $500 million in research, development, test and evaluation for the electronic warfare area.)[84] In each case, resources are spread among several grassroots science and technology efforts, a smaller set of advanced development and demonstration activities and an even smaller number of system acquisitions. In the area of DE weapons, there are competing developmental demands and competing programmatic stovepipes — which reduces the prospects for transitioning *any* successful development to the warfighter.

Relative to other capability areas, defense spending on DE weapons is modest. In comparison, DOD spent in fiscal year 2014 on the order of $9 billion on procurement of conventional missiles and munitions and an additional $8.2 billion for missile defense procurement, in addition to hundreds of millions spread across the services in associated RDT&E.[85] For example, DOD spent roughly $73 million on RDT&E and an additional $405 million to procure the mature Advanced Medium-Range Air-to-Air Missile; this exceeds the annualized sum of the entire DE weapons portfolio. In turn, $910 million in RDT&E expenditures for the Aegis ballistic missile defense system is more than twice DOD spending on all DE weapon activities. Similarly, modifications to the Trident II submarine-launched ballistic missile cost approximately $1.45 billion in combined fiscal year 2014 RDT&E and procurement activities — roughly 3.5 times the total spent on the full-range of DE weapons-related activities. In short, the department's resource allocation profile does not suggest it currently sees high value in DE weapon systems or anticipates near-term success in this area.

While DOD can benefit from global technology trends that affect the development prospects for DE weapons, the market for military-grade DE weapons is at its core a monopsony. Assistant Secretary of Defense Katrina McFarland has implored private industry to invest independent research and development in such areas as electronic warfare to "create for us an advantage," and she has argued that "the firms that make strategic investments now will succeed."[86] Yet, the limited demand signals industry has received from its defense customers in the DE weapons area to date may undercut this proposition. It is hard to see the financial incentive for businesses to invest in technology maturation on their own when a significant future acquisition effort is questionable. And while the record suggests that many companies seek to enhance their research and development posture during recessionary times, the recent evidence also suggests that companies have become more conservative in their research and development practices — especially companies in industries facing prolonged market uncertainty.[87] In this context, the Center for Strategic and International Studies found that from 2012 to 2013, overall defense-funded contract obligations declined by 16 percent, a sequester-induced decline with disproportionate impact on the research and development accounts.[88]

If DOD wants to aggressively pursue DE weapons as part of a broader offset strategy, it will need both to highlight the importance of this area and to make available sufficient resources if it is to achieve the desired programmatic outcomes. At this point, the department neither spends enough to underscore the importance of developments in this area nor otherwise incentivizes industry to spend scarce internal resources for a market that may not exist in the near-term to midterm. For operationally significant DE weapons to become reality in the near-term to midterm, DOD should increase by two to three times its current level of HEL-related spending annually and increase by five to 10 times its HPM and related radiofrequency weapon investments. All-in, this would bring total DOD DE weapon spending to roughly $1.3 billion. Scaled for inflation, this is roughly half what DOD spent on high-energy lasers when the Berlin Wall collapsed in 1989.

4. HARVEST THE LOW-HANGING FRUIT — GET IT IN THE FIELD.

The upside of several concurrent technology development activities is that there may be one or more near-term opportunities to demonstrate the technical capability and operational utility of developmental systems. The Navy's Laser Weapon System being tested aboard the *USS Ponce* is at the head of the queue. Based on the Navy's reportedly promising November 2014 Persian Gulf tests, the 33-kilowatt system establishes a reasonable foundation to proceed with development of a scaled-up 100- to 150-kilowatt (or higher) system.[89] Rear Admiral Matthew Klunder, former chief of naval research, has argued that such a system could provide high-value counterdrone, counterboat and combat identification capabilities. Once it has achieved this higher-power metric at acceptable beam quality, the Navy should consider limited-quantity procurement for operational deployment to a relevant operational theater. In a similar vein, once the Air Force-DARPA High Energy Liquid Laser Area Defense System demonstrates in the laboratory its 150-kilowatt output metric at acceptable beam quality, it should be tested in an operationally relevant environment. As a near-term alternative, should the Air Force seek enhanced self-protection options for tactical aircraft, it could explore modifications to the existing, comparatively low-power directional infrared countermeasures (DIRCM) systems used aboard some large airframes.

At the same time, at least two recent high-power microwave systems have already been successfully demonstrated. The millimeter wave counterpersonnel Active Denial System can, in theory, play a valuable nonlethal force protection role at fixed sites or on an expeditionary basis — provided policy concerns associated with counterpersonnel DE weapon use can be effectively addressed. (Its lack of operational use has stemmed from policy considerations, not technical immaturity.) The other mature system, the CHAMP high-power microwave cruise missile, should also be considered for limited-quantity procurement since it could provide a unique, near-term unmanned counterelectronic capability and a potential escalation (or de-escalation) option for theater commanders. Air Force Research Laboratory commander Major General Thomas Masiello reported that the high-power microwave cruise missile proved "highly, highly successful" in its 2012 testing.[90] But if Air Staff and/or Air Combat Command leadership have instead concluded the weapon requires additional maturation, DOD should consider accelerating development of next-generation solid-state high-power microwave devices on platforms such as the Joint Air-to-Surface Standoff Missile or the Tomahawk Land Attack Missile, both of which may have sufficient payload volume to generate the desired effects at an acceptable range. With respect to other ground systems, should the current Army or Marine Corps developmental high-energy laser systems ultimately reach a point of operational maturity similar to the Navy's Laser Weapon System, those services might also consider a limited — and preferably joint — procurement. Alternatively, once the Air Force-DARPA High Energy Liquid Laser is proven in the field, the Army and Marine Corps should explore whether it could be successfully adapted for ground (fixed or mobile) use. Should an operational need warrant more rapid action, they should assess whether other ground-based systems, such as Israel's Iron Beam or Lockheed Martin's prototype Area Defense Anti-Munitions system, meet their requirements.[91]

5. EYES ON THE PRIZE — INVEST FOR LONGER-TERM SUCCESS.

DOD conducts research and engineering to create technology surprise for potential adversaries.[92] Directed energy, along with other electric-weapon technologies, such as the electromagnetic railgun, has significant *potential* for cost-effective missile defense and other challenging missions.[93] Yet, while DE weapons could productively address the full range of operational military challenges, current developments largely cater to the lower end of the threat spectrum. And, although substantially more capable high-energy laser and HPM systems appear possible, there is no overarching DOD plan to groom next-generation DE weapons for these more difficult operational tasks. The Department of Defense faces high-end threats for which DE weapons could become a preferred option, if substantially more capable DE weapon solutions can be successfully developed. Significantly enhanced fixed-site defenses for forward operating bases, an improved ability to provide for fleet defense in contested areas, and reliable and effective strategic defense against ballistic and cruise missiles in the homeland and in theater rear areas are a few compelling examples. By enabling a cost-effective approach to ballistic missile defense, they could invert key anti-access challenges, enabling the U.S. military to operate more effectively within an adversary's threat ring, enhancing U.S. power projection opportunities and improving homeland defenses.

A flattening world meets accelerating time, which together conspire both to erode longevity in technological superiority and to facilitate more rapid development of next-generation technologies.

At the end of the day, if substantially more capable laser and/or microwave systems are required to prosecute some of the most daunting operational challenges — such as cruise or ballistic missile defense — the department must invest substantially in these areas. While the technical *performance* of the 1980s-era developmental systems left much to be desired, their underlying *logic* was quite defensible. The central issue is whether the state of technology three decades later may finally enable a different outcome; or, if not, what must be achieved for such large-output capabilities to become operational reality. Clearly, DOD can benefit from underlying trends in key technology areas, some of which are driven by the commercial sector at the material, component or subsystem level for civil applications. Ultimately, however, the market for high-output DE weapon systems is limited and technological serendipity is not likely. Because there are few alternative drivers, the Defense Department must actively groom its preferred cadre of DE weapon systems. To achieve the types of higher-output DE weapons that would be truly game-changing requires investments in lethality, susceptibility and vulnerability testing, material science and key component technologies, high-fidelity modeling and simulation and operationally informed experimentation. Ultimately, specific investments should be driven by technological maturity and potential opportunity in a context of compelling warfighter need. DOD should not simply return to high-dollar, high-risk ventures like the Airborne and Space-Based Laser programs, but rather steadily ramp up its investments to mature and, as appropriate, acquire those high-energy laser and high-power microwave weapons that deliver effective capability. It must actively continue to push the envelope — expanding the art-of-the-possible for daunting defense missions.

6. CONDUCT A NET ASSESSMENT AND ACTIVELY MONITOR FOREIGN DEVELOPMENTS.

Globalization both enables and threatens U.S. technological advantages in the civil and military spheres. Although the United States accounts for about one-third of the world's aggregate research and development spending, the trend lines show that China, Japan, South Korea and other states account for an increasing share year over year. By 2022, China may overtake the United States in terms of total research and development spending.[94] On the one hand, this suggests that it will become increasingly difficult to develop and sustain competitive advantages in a globalizing marketplace. On the other hand, this provides an opportunity to adopt, learn from or otherwise tap into foreign scientific and technical developments as a way to truncate lengthy and cumbersome weapon development processes. In both cases, the underlying trends underscore a continuing compression in time and space for technology, place a premium on speed and agility, elevate technology-enabled risks and require modernized research and acquisition practices. In short: A flattening world meets accelerating time, which together conspire both to erode longevity in technological superiority and to facilitate more rapid development of next-generation technologies.

Among the implications of this phenomenon is the growing potential for technical surprise. Potential U.S. adversaries benefit from the same technology trends and, in some cases, aggressively seek to counter U.S. military superiority. (The House Armed Services Committee similarly called for DOD to report in fiscal year 2014 on foreign DE threats to U.S. military systems.)[95] To better understand the evolving global DE technology landscape, the department should conduct a net assessment on directed energy. To be most useful, such an assessment would:

- Be informed both by intelligence specialists and technologists;
- Underscore both key technology advances and continuing capability gaps;
- Highlight key vulnerabilities and potential countermeasures;
- Identify key risks and challenges to the U.S. defense posture; and
- Present options for the policy, operational and acquisition communities.

Not only would such an effort mitigate the potential for surprise, but it would also help diminish its consequences. A net assessment would provide a credible starting point for measures designed both to bolster a deterrence-by-denial strategy and to strengthen crisis stability, escalation and compellence options. It should also help the department determine, for example, whether (and how seriously) to pursue space-related directed-energy weapon options.

The nation's nuclear weapon laboratories and their defense counterparts have a special role to play in providing credible, technically informed warning of foreign DE weapon developments. The national science and technology base cuts across the national laboratories, including Lawrence Livermore, Sandia and Los Alamos; the military laboratories and warfare centers, such as the Air Force Research Laboratory at Kirtland Air Force Base, Naval Surface Warfare Centers at Dahlgren and China Lake; and the defense industry. U.S. efforts to maintain — let alone fully exploit — its national technology base are not commensurate with the pace, breadth and prospective impact of foreign directed-energy developments, particularly with respect to radiofrequency weapon technologies. As part of the proposed resource plus-up, the Defense Department, working with its interagency partners, should consider developing an integrated national DE research program. As a starting point, providers and participants should:

- Conduct a net assessment comparing U.S. and foreign DE weapon developments, trend lines and prospective future directions;
- Identify and prioritize RDT&E efforts in support of identified and emergent national priorities;
- Advance foundational DE science and technology;
- Provide necessary offensive and defensive

capabilities to federal stakeholders such as the departments of Energy, Justice and Homeland Security;

- Make recommendations to mitigate the prospect for and impact of technology surprise; and
- Lay the foundation for a more robust public-private DE weapon innovation partnership.

To ensure close alignment with priority national missions, these efforts should be overseen by a steering committee made up of national agency leadership, by a designated executive agent or by another oversight mechanism.

7. PUT DE WEAPONS IN CONTEXT — A BROAD, REINFORCING SET OF ELECTROMAGNETIC SPECTRUM CAPABILITIES.

Whether or not DOD ultimately opts to identify a champion, establish a separate community of interest focused on directed energy or otherwise highlight a growing role for DE weapons in the emergent defense posture, it is equally important to ensure that it does not become just another technology stovepipe. DE weapons stand on their own merits — individual systems designed for discrete functions. They are not silver bullets, but rather one of a broader set of tools in the warfighter's toolbox. While DE weapons draw upon doctrinal concepts such as fires and protection, for now they are binned under an electronic warfare umbrella; in turn, both electronic warfare and computer network operations are subordinate to the broader information operations area.[96] Programmatically, however, there has been insufficient cross-domain coordination, little identifiable leverage and few operational synergies realized to date. A systems approach is needed — an integrated, cross-domain effort that delivers a warfighting capability sum greater than its constituent parts.

DE's place in the broader mix of nonkinetic technologies available to the warfighter warrants special consideration. Historically, the defense community has pursued DE weapon development as a special capability, a counterpart to (or surrogate for) well-understood kinetic weapons. For example, just as the Airborne Laser was developed as a dedicated laser weapon platform for missile defense, the Air Force reportedly seeks for its next-generation fighter aircraft the ability to incorporate laser weapons for air-to-air engagement.[97] As DE weapons are introduced into the inventory, the department should consider developing more robust DE-focused doctrine. Other nonkinetic technologies that leverage the electromagnetic spectrum are typically viewed less as "weapons" than as "enablers" that fit within a broader force package. Cyber and electronic warfare technologies are two important operational enablers. The growing convergence between these and DE weapons suggests considerable crossover potential, as "computer and telecommunication networks are becoming one and the same."[98] To date, the comparative immaturity of DE weapon systems has prevented systematic development of a more holistic, and likely more effective, approach to electromagnetic spectrum weapon technologies. Taken together, the parallel advances in DE weapons, cybersecurity tools and other electronic warfare technologies could — if operated as a system — provide the nation an important, if dynamic, qualitative military edge.

Applied against theater command and control, integrated air defense, communication or other possible high-interest military targets, their integrated capabilities could enable a more sophisticated array of nonkinetic strike options operating along different portions of the electromagnetic spectrum. Each nonkinetic tool has a place in the system and, working in combination, should advance the U.S. ability to project power at reduced operational risk in anti-access and area-denial settings. An enhanced focus on combined directed energy/electronic warfare/cyberexperimentation and wargaming would help DOD appropriately adjust its warfighting concepts, doctrinal approaches, technology development strategies and operational planning.

8. PLAN FOR SUCCESS — DE WEAPONS ENTERING THE INVENTORY.

Finally, although the record for directed-energy weapons to date leaves much to be desired, DOD should plan for success. As a starting point, current-generation pathfinders may perform niche operational roles or add incrementally to combat capabilities. But if fielded, their more significant contribution will be cultural and organizational in nature. Integrating DE weapon capabilities as elements of a broader force package will require adjustments across the doctrinal, organizational, training, logistics, policy and other fronts. Taken together, they would put high-power microwave and high-energy laser systems in the service of identifiable warfighter needs. They could provide the early, tangible measures to "demystify" new DE weapon technologies.[99] They would be consistent with the crawl-walk-run approach suggested by the National Academy and others.[100] And they could go a long way toward bridging the legacy technologist/operator schism highlighted by the Defense Science Board and external analysts.[101]

More broadly, the continuing development and eventual deployment of more capable DE weapon systems may diminish operational risk, create improved warfighting options and ultimately enable new courses of action. Because of that, directed-energy technologies should factor into tabletop, command post and other Department of Defense exercises in relevant mission areas. They should become integral to DOD strategy and joint doctrine, command-focused operational and contingency planning and service concepts of operation. While there is a risk to getting the cart too far ahead of the horse, the status quo highlights an equal risk: uncoupling the horse from the cart just as the horse is preparing to run. Properly executed, leadership and forces will be prepared as new capabilities — groomed by DOD — become available. This is the essence of a competitive and sustaining military advantage and fundamental to the offset strategy sought by Defense leadership.

ENDNOTES

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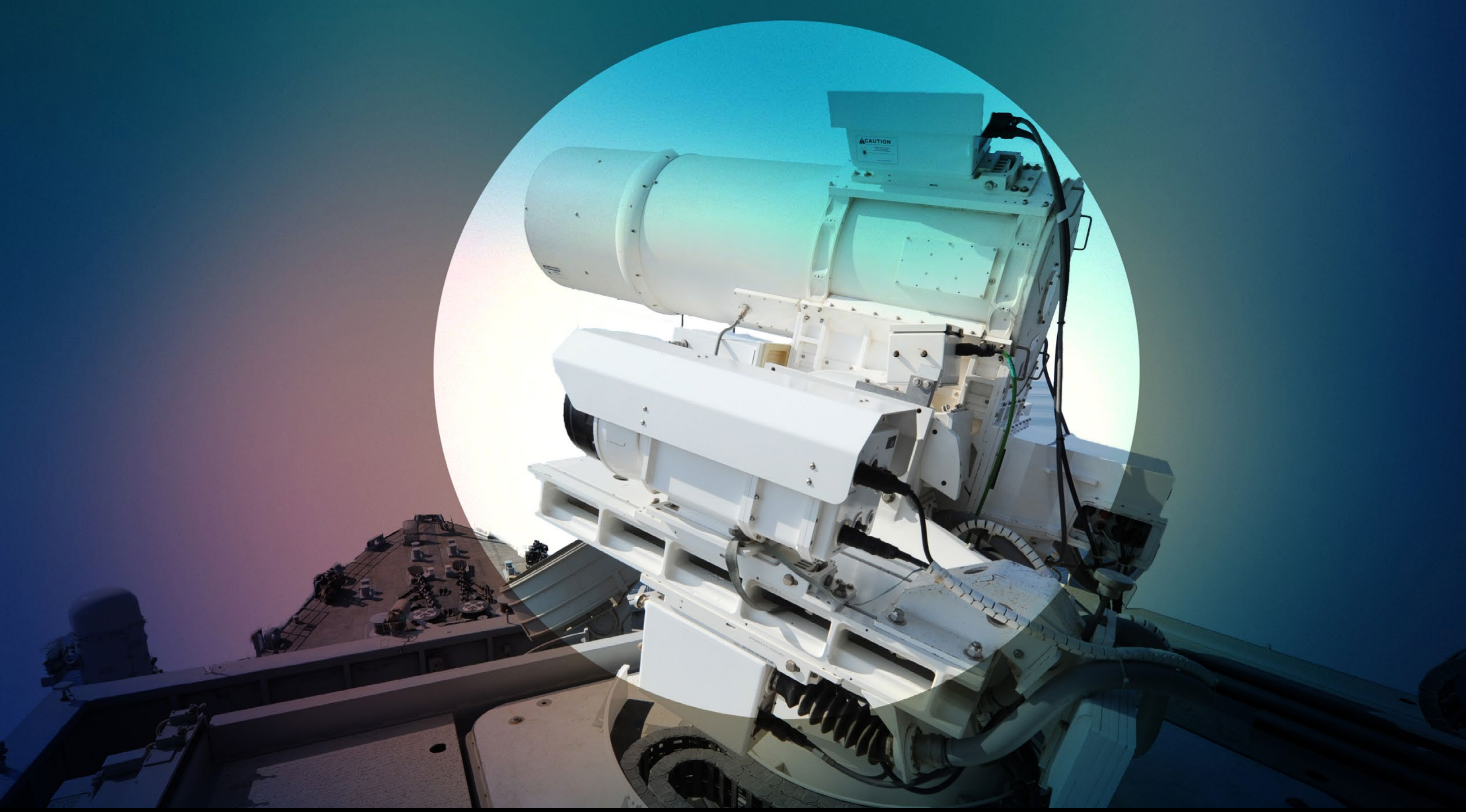

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