United States Government Accountability Office

Report to Congressional Committees

April 2023

DIRECTED ENERGY WEAPONS

DOD Should Focus on Transition Planning

GAO-23-105868

GAO Highlights

Highlights of GAO-23-105868, a report to congressional committees

April 2023

DIRECTED ENERGY WEAPONS

DOD Should Focus on Transition Planning

Why GAO Did This Study

DOD spends about $1 billion annually on directed energy—concentrated electromagnetic energy—weapons, including high energy lasers and high power microwaves. DOD has pursued these potentially transformative technologies for decades because they could provide considerable advantages. They can deliver destructive or disruptive effects to targets at the speed of light and have potentially significant advantages over kinetic weapons, such as missiles, including lower per-use cost.

A Senate report includes a provision for GAO to review DOD's directed energy work including the technologies, industrial base and related infrastructure, and transition efforts. This report (1) describes the status of DOD and military department directed energy weapon efforts, and (2) assesses challenges with transitioning directed energy weapon efforts from prototyping. GAO selected seven directed energy efforts to obtain insights on a variety of types of efforts, intended uses environment, and military departments. GAO reviewed DOD documentation and interviewed DOD officials and industry representatives.

What GAO Recommends

GAO is making four recommendations to DOD, including that the Navy and the Air Force develop transition agreements between prototype developers and planned transition partners. DOD concurred with three recommendations and partially concurred with one recommendation. GAO continues to believe that the recommendation should be fully implemented.

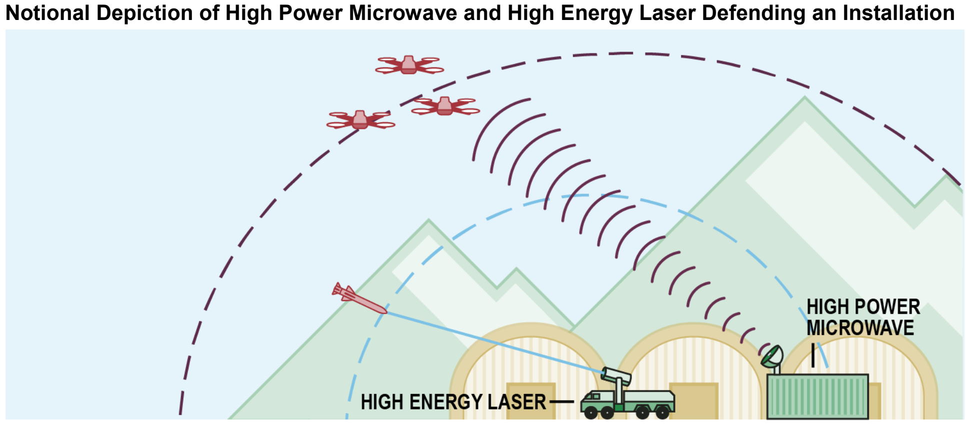
View GAO-23-105868. For more information, contact Jon Ludwigson at (202) 512-4841 or LudwigsonJ@gao.gov.

What GAO Found

The Department of Defense (DOD) is currently developing directed energy weapons with the goal of defeating a range of threats, including drones and missiles. However, GAO found that, even as DOD makes progress developing these capabilities, its efforts to transition prototypes to acquisition programs face challenges.

DOD and the military departments have efforts underway to develop directed energy weapons. For example, DOD and military departments developed multiple laser weapon system demonstrators and prototypes, which have been used in live fire demonstrations to successfully shoot down drones. DOD and the military departments are also developing higher-powered laser weapons to counter bigger threats. Additionally, the departments developed a range of high power microwave capabilities for purposes such as engaging missile or drone swarm attacks against a military base.

Notional Depiction of High Power Microwave and High Energy Laser Defending an Installation



Source: GAO analysis of Department of Defense information. | GAO-23-105868

However, DOD has long noted a gap—sometimes called "the valley of death"—between its development and its acquisition communities that impede technology transition. For example, the acquisition community may require a higher level of technology maturity than the development community is able to produce.

For prototypes that a military department expects to eventually transition to a new or existing acquisition program, it needs to identify a transition partner that can support the further development of the new technology. To support transition, the Army developed a detailed plan describing schedules and stakeholder roles to build supporting activities around the use of directed energy weapons and early capabilities documents. However, while the Navy fielded several directed energy weapon prototypes and identified a potential transition partner, it does not have documented transition agreements for the directed energy programs that GAO reviewed. The Air Force has not consistently prioritized establishing transition partners, which makes planning for future transition even more challenging. Without these transition planning steps, the Navy and Air Force risk developing directed energy weapons that may be misaligned with operational needs.

Contents

Abbreviations

AFRL	Air Force Research Laboratory
DE	directed energy
DOD	Department of Defense
HEL	high energy laser
HPM	high power microwave
kW	kilowatt
PEO	Program Executive Office
STP	soldier touch point
TRL	Technology Readiness Level
UAS	uncrewed aerial systems

U.S. GOVERNMENT ACCOUNTABILITY OFFICE
441 G St. N.W.
Washington, DC 20548

April 17, 2023

Congressional Committees

Directed energy (DE) is a potentially transformative technology for the military. Unlike kinetic weapons, such as bullets and missiles that generally rely on physical impact to attack a target, DE weapons use concentrated electromagnetic energy to deliver destructive or disruptive effects to targets at the speed of light. In addition, DE weapons have potentially significant advantages over kinetic weapons, including lower per-use cost. In 2018, the Department of Defense (DOD) identified DE as one of 11 technologies critical to enabling the 2018 National Defense Strategy. Over the past 3 years, DOD has reported spending an average of $1 billion annually on DE weapons development efforts. According to DOD, the goal for current DE development efforts is to improve the capability to defeat a range of threats, including drones and cruise missiles, through an integrated and layered defense with DE weapons complementing kinetic weapons.[1]

Senate Report 117-39 accompanying the National Defense Authorization Act for Fiscal Year 2022 includes a provision for us to review DOD's DE work, including the technologies, industrial base and related infrastructure, and transition efforts.[2] This report (1) describes the status of DOD and military department DE weapon efforts; and (2) assesses the challenges with transitioning DE weapon efforts from prototyping and actions the military departments have taken to mitigate the challenges.

To describe the status of DE weapons efforts, we reviewed the DOD's 2021 Directed Energy Roadmap, the fiscal year 2022 and 2023 President's Budgets, and briefings provided by DOD and the military departments. To assess the challenges with transitioning DE weapon efforts from prototyping, we selected a non-generalizable sample of seven DE weapon efforts from the Army, Navy, and Air Force based on criteria such as the type of technology and the intended use environment to review a variety of efforts. For each of these seven efforts, we reviewed relevant documentation and compared development activities associated

[1]To better defend against threats like cruise missiles, an integrated and layered defense includes sensors to detect and track threats, threat interceptors like surface-to-air missiles, guns, or directed energy, and a command and control system.

[2]S. Rep. No. 117-39, at 154.

with these programs to GAO's prior work on technology transition, GAO's leading practices for product development, and DOD's guidance on prototyping.

For both objectives, we conducted site visits and interviewed officials within DOD and the Army, Navy, and Air Force responsible for DE weapon efforts to understand the status of the systems and any plans to transition these systems from prototyping to acquisition programs. See appendix I for a more detailed description of our objectives, scope, and methodology. In addition, see a list of Related GAO Products at the end of this report.

We conducted this performance audit from February 2022 to April 2023 in accordance with generally accepted government auditing standards. Those standards require that we plan and perform the audit to obtain sufficient, appropriate evidence to provide a reasonable basis for our findings and conclusions based on our audit objectives. We believe that the evidence obtained provides a reasonable basis for our finding and conclusions based on our audit objectives.

Background

DE Weapons Technology

For decades, DOD has been developing DE weapons technologies that use electromagnetic energy to deny, degrade, damage, destroy, or deceive enemy weapons, equipment, facilities, and personnel. For many years, DOD's focus on DE weapons development was through chemical laser weapons development. Most notably, DOD developed the Airborne Laser Program, a chemical laser that achieved destructive power output. But the weapon required the use of hazardous chemicals to generate power, had significant issues with size, weight, and power due to heavy physical components, and required a large team of 15 to 18 operators. More recently, DOD's laser development efforts have focused on solid-state lasers, which use a medium such as a fiber-optic cable to carry the generated electromagnetic energy, and are lighter and can be operated by a single person.

The two primary DE technologies, high energy lasers (HEL) and high power microwaves (HPM), have some similarities. For example, HEL and HPM both project electromagnetic energy to affect their targets, require a power source, must be connected to a command, control and communication center, and are mounted on a platform of some kind.[3] However, the two technologies also have some fundamental differences.

HEL tightly focuses a beam, or beams, of energy on a single target to damage sensors or cause destructive heating. HEL systems include components such as

- adaptive optics to compensate for atmospheric interference to improve HEL range,
- sophisticated sensors for identifying and tracking targets,
- advanced thermal management systems to cool the weapon as it is in use, and
- software modeling to assist with identifying aimpoints on targets.[4]

By contrast, HPM radiate waves of energy that can disrupt or damage electrical components of multiple targets within the entire targeted area simultaneously. HPM systems include components such as

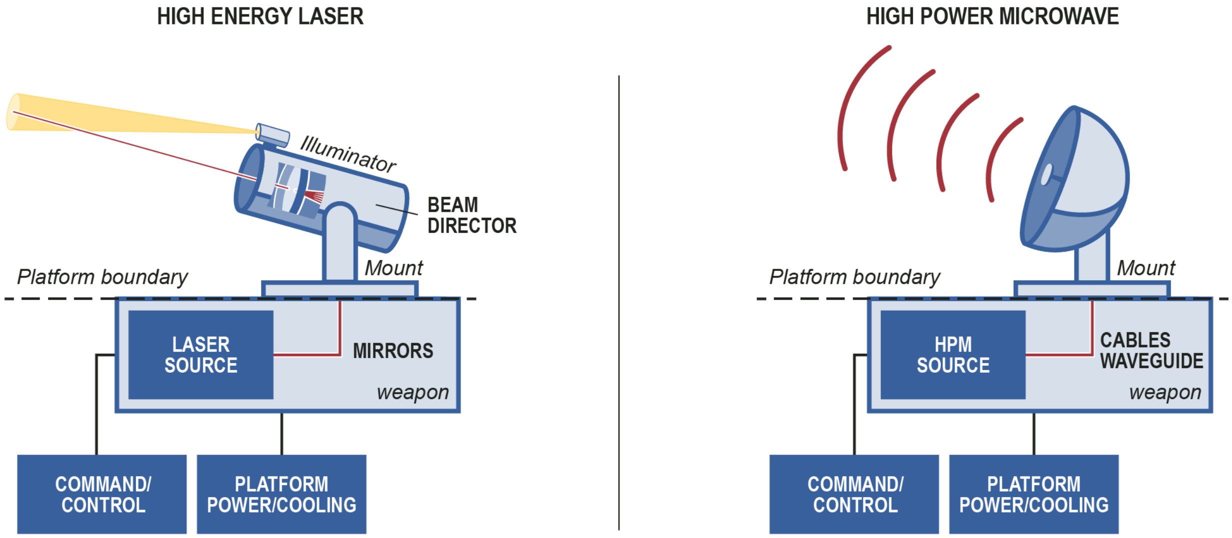
- capacitators to enable the weapon system to store and release energy,
- an antenna to direct the microwaves toward the target area, and
- a vacuum technology to reduce the amount of trapped gasses within the device to support the generation of high power microwaves.

Figure 1 provides an illustration of the basic design of HEL and HPM weapons.

[3]DOD reports command, control, and communications systems are fundamental to all military operations, delivering the critical information necessary to plan, coordinate, and control forces and operations across the full range of DOD missions.

[4]An aimpoint is a precise point, based on an area of vulnerability, associated with a given target and assigned for a specific weapon to achieve the intended objective and level of destruction.

Figure 1: Illustration of High Energy Laser (HEL) and High Power Microwave (HPM) Systems



Source: GAO analysis of Department of Defense information. | GAO-23-105868

Table 1 describes in further detail some of the key differences in characteristics between HEL and HPM systems.

Table 1: Characteristics of High Energy Laser (HEL) and High Power Microwave (HPM) Weapons

Features	High energy laser	High power microwave
Function	Delivers energy to affect physical elements of a target like wings or optical sensors. HEL beams can cut through materials such as steel and aluminum in a matter of seconds. HEL systems engage targets one by one.	Delivers energy to affect electronics by overwhelming critical components intended to carry electrical currents such as circuit boards, power systems, or sensors. HPM systems engage targets over an area within its wider beam and can penetrate solid objects.
Physical characteristics[a]	Uses electromagnetic power measured in kilowatts directed, combined, and focused into a beam. Lasers are usually infrared and visible light.	Measured in gigahertz with wavelengths 10,000 times longer than lasers.
Testing	The effect of lasers changes according to environmental and other factors, making testing in an operational environment over a broad range of conditions particularly important.	DOD officials report that the effects of HPM are “nearly linear” so that testing can be done in a lab where tests at small scale and lower power levels can accurately predict effects at higher power levels. Full system testing is important to understand component limitations outside of a laboratory environment.

Lethality	Lethality depends on the amount of energy transferred which, in turn, is a function of the amount of energy delivered to the target and time on target. The amount of energy that can be delivered to the target depends on power output, purity, and concentration of energy on the target (beam quality), target range, and physical or atmospheric obstructions. The time on target depends on tracking the specific aimpoint on the target and continuing to keep the laser focused on it.[b]	Lethality depends on peak power output, the rate of microwave pulses, and the frequency used. HPM waves can travel through non-conductive solid material such as walls. HPM requires matching to specific types of targets and uses specific radio frequencies that will affect wires or circuit boards.

Source: GAO analysis of Department of Defense (DOD) and military department documents, and information provided. | GAO-23-105868

[a]Electromagnetic energy includes radio waves, microwaves, infrared, visible light, ultraviolet, x-rays, and gamma rays. Laser is an acronym for "light amplification by stimulated emission of radiation." Diffraction of any electromagnetic radiation beam is based on the wavelength and aperture size. 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. Lasers are preferred in specific scenarios because of minimal diffraction.

[b]The ability to keep the laser on target typically refers to tracking and "jitter control." Tracking is the weapon's ability to follow its target. Jitter control refers to the HEL's ability to focus the beam on the specified target area.

Potential Benefits of DE Weapons

Some advantages of DE weapons include the following:

Low cost per shot. While the upfront cost of some DE weapons can be significant, DE weapon systems' costs per engagement can be much lower. For example, DOD officials said that the cost to fire a DE weapon is approximately the cost of fuel needed to generate the system's power for firing and cooling, or about $1-$10 per engagement. By comparison, defensive missiles can cost millions of dollars per shot.[5]

Magazine depth. Because DE weapons do not rely on kinetic ammunition and are electrically recharged, they do not require mechanical reloading. Instead, they rely on power and cooling supported by a platform's overall power supply. HEL can repeatedly fire as long as the systems can generate sufficient power and manage the heat created by firing. HPMs do not generate as much heat as HELs and are able to continue firing with sufficient power. Platforms use fuel to generate the necessary electrical power and cooling.

HPM time on target. HPM may have an immediate effect on a target with systems that DOD officials say fire the equivalent of hundreds or thousands of shots per second.

[5]For example, Army budget materials report that the Patriot Advanced Capability 3 Missile Segment Enhancement, which can intercept ballistic missiles, cruise missiles, and uncrewed aerial systems, costs approximately $4.1 million per unit for fiscal year 2023.

Possible Limitations of DE Weapons

Some possible limitations of DE weapons include the following:

Distance to target. HPM and HEL are generally less effective the farther they are from the target. HPM power on target decreases over range. For HEL, distance may cause beams to be distorted, or energy may become absorbed by particles and water vapor in the air.

Atmospheric effects. The effectiveness of DE weapons can be affected by environmental factors. For example, HEL has reduced effectiveness under certain atmospheric conditions, such as severe wind turbulence. Air particles and water vapor can also absorb or distort HEL beams. To mitigate this issue, a DOD official said DOD takes steps to select wavelengths that are less affected by water vapor. Adaptive optics help HEL weapons remain focused and "see" through atmospheric turbulence. Still, there are environmental conditions where DE weapons would not be effective and could not be used by the warfighter. DOD officials said HPMs that operate at high frequency and long range are also affected by the environment in similar ways to communication devices already in use, such as radios.

Delicate components. Because HELs involve sending light through optical lenses and off mirrors, any contaminants or debris on those optics will interact with the beam and potentially damage the lens. For example, debris on the lens can damage the lens when the laser is fired, because the particle on the lens will capture some of the heat. Because of this, components are maintained or fixed in a specialized facility called a clean room to avoid contamination.[6]

Technology Development Process

For decades, DOD has prioritized investing in early-stage research and development of technologies. As part of the DOD effort to initiate, rather than react to, strategic technological surprises, DOD and the military departments invest in research and development to evaluate the feasibility or usefulness of a technology or concept.[7] DOD's science and technology community—including DOD research laboratories and test facilities, industry, and academia—conducts initial research, development, and testing of new technologies to evaluate the potential to

[6]A "clean room" is an actively cleaned and isolated space engineered to reduce contamination from airborne particles. Clean room classifications vary by levels of airborne particles within the area.

[7]GAO, *Defense Advanced Research Projects Agency: Key Factors Drive Transition of Technologies, but Better Training and Data Dissemination Can Increase Success,* GAO-16-5 (Washington, D.C.: Nov. 18, 2015).

improve military operations and strive for technological superiority over potential adversaries.

Establishing funding for technology development may include a number of challenges and may take years. We have reported that it may be challenging for new technologies to compete against established acquisition programs in obtaining funding.[8] Lengthy budgeting timelines also pose a challenge to developing new technologies aimed at responding to emerging threats. For example, under DOD's programming, budgeting, and execution process, a project idea may take at least a year and a half to get initial funding after the idea is first conceived.

As part of the technology development process, DOD groups research and development into seven budget activity categories for its budget estimates and the President's Budget. The categories follow a mostly sequential path for developing technologies, ranging from basic research (funded through budget activity 6.1) to operational system development (budget activity 6.7). Requested funding for prototyping is mostly found in budget activities for advanced technology development (6.3) and advanced component development (6.4). Requested funding in budget activity 6.3 is not directly tied to acquisition programs, whereas budget activity 6.4 is typically associated with an acquisition program. Specifically, 6.4 funding is for advanced component development, system specific evaluations of integrated technologies, representative models, or prototype systems in a realistic operating environment. Activities under this level of funding focus on proving component and subsystem maturity prior to integration into major systems.

Prototyping

A key component of technology development is prototyping. Prototypes allow for rapid learning and accelerated demonstration of the value of new concepts, technologies, components, systems, and applications earlier in a technology development process than typically would have been possible. The DOD Prototyping Guidebook defines prototyping as a model built to evaluate and inform feasibility or usefulness.[9] Prototypes

[8]For more on DOD's budgeting process for technology development, see GAO, *Weapon Systems: Prototyping Has Benefitted Acquisition Programs, but More Can Be Done to Support Innovative Initiatives,* GAO-17-309 (Washington, D.C.: June 27, 2017).

[9]Department of Defense, *Department of Defense Prototyping Guidebook,* Version 2.0 (Washington, D.C.: November 2019).

can be described relative to when they occur in a program's life cycle, including

- Conceptual—supports proof of concept analysis and may be demonstrated in a lab environment.
- Development—explores the technical feasibility of capability and may explore its operational value and is demonstrated in a relevant environment.
- Operational—offers technical and operational value and upon completion can be employed in an operational environment.

Prototyping is a tool to support the development of innovative technologies—that may be more risky than known designs or existing technology—prior to investing in an acquisition program. We have previously reported on two types of innovation: incremental and disruptive.[10] Incremental innovation seeks to gradually improve existing products and capabilities. Disruptive innovation attempts to shift the balance of military power by providing new capabilities, potentially unforeseen by military departments. The capabilities can be a result of new technologies, new ways to integrate existing technologies, or changes to how systems are employed. Examples of potentially disruptive technologies include DE, artificial intelligence, and hypersonics.[11]

The DOD Prototyping Guidebook states that successful prototyping begins with effective planning. Planning should include a clear articulation of the problem or need to be addressed, a description of the future decision to be made, the data to be generated by the project, and an explanation of how the data will be used to inform a future decision.

Technology Transition

Once technologies are determined to be sufficiently mature, the acquisition community typically manages product development, in which

[10]GAO-17-309.

[11]GAO, *Hypersonic Weapons: DOD Should Clarify Roles and Responsibilities to Ensure Coordination across Development Efforts*, GAO-21-378 (Washington, D.C.: Mar. 22, 2021); and *Artificial Intelligence: Status of Developing and Acquiring Capabilities for Weapon Systems,* GAO 22-104765 (Washington, D.C.: Feb. 17, 2022). GAO has additional ongoing work on artificial intelligence.

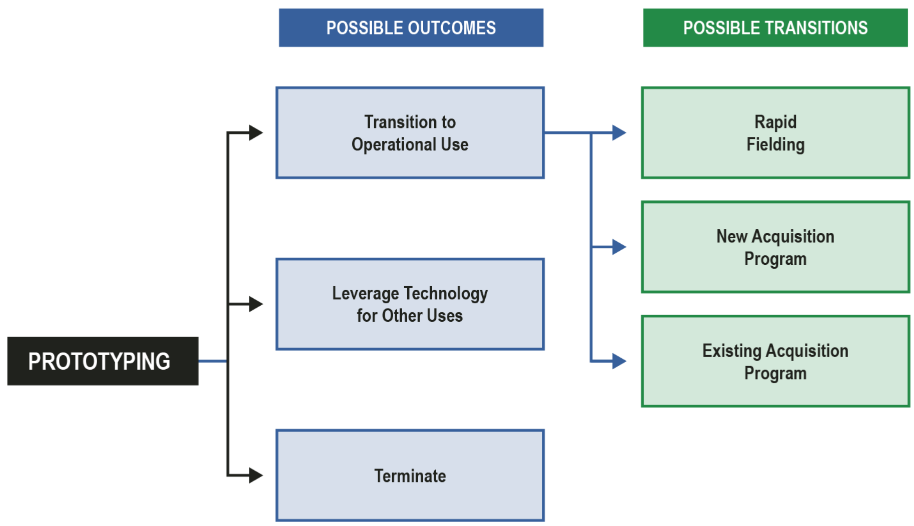
technologies are further advanced and system development begins.[12] Although not precisely defined, technology transition to an acquisition program generally occurs at the point when advanced technology development ends and new product development begins.[13]

Prototyping efforts may result in different outcomes including transitioning successfully demonstrated technologies to operational use, leveraging the technology for other uses, or terminating unsuccessful efforts and associated technology research. Transitioning the prototype to operational use may include rapid fielding of the effort, transitioning the technology for use by an existing acquisition program, or beginning a new acquisition program. Figure 2 illustrates these potential transition pathways.

[12]A way of describing technological maturity is through Technology Readiness Levels (TRL), based on assessed maturity and numbered 1-9. TRLs range from a point where basic principles are observed (TRL 1) to full systems demonstrated in an operational environment under operational mission conditions (TRL 9).

[13]Advanced technology development can encompass subsystem or component evaluation in a laboratory or relevant environment, and new product development may involve system or prototype development and demonstration for use in an operational environment.

Figure 2: Department of Defense Potential Prototype Outcomes



Source: GAO analysis of Department of Defense information. | GAO-23-105868

For transitioning from prototyping to operational use, the DOD Prototyping Guidebook states that transition planning should be initiated as early as possible through collaborative efforts by the innovator, project management, and the warfighter. This collaboration is essential for clearly understanding the need and criteria to be met by the prototype for a successful demonstration in an operational environment. Our work also found that active collaboration with potential transition partners contributed to transition success.[14]

Our work found that DOD recognizes the difficulties involved in transitioning technologies to operational use.[15] DOD has long noted the existence of a chasm between its technology community and its acquisition community that impedes consistent technology transition. Department insiders often refer to this as the “valley of death,” which exists because the acquisition community may require a higher level of technology maturity than the science and technology community is able to

[14] GAO-16-5.

[15] GAO-13-286, *Defense Technology Development: Technology Transition Programs Support Military Users, but Opportunities Exist to Improve Measurement of Outcomes,* (Washington, D.C.: Mar. 7, 2013).

fund and develop. Technologies may not leave the lab for several reasons including

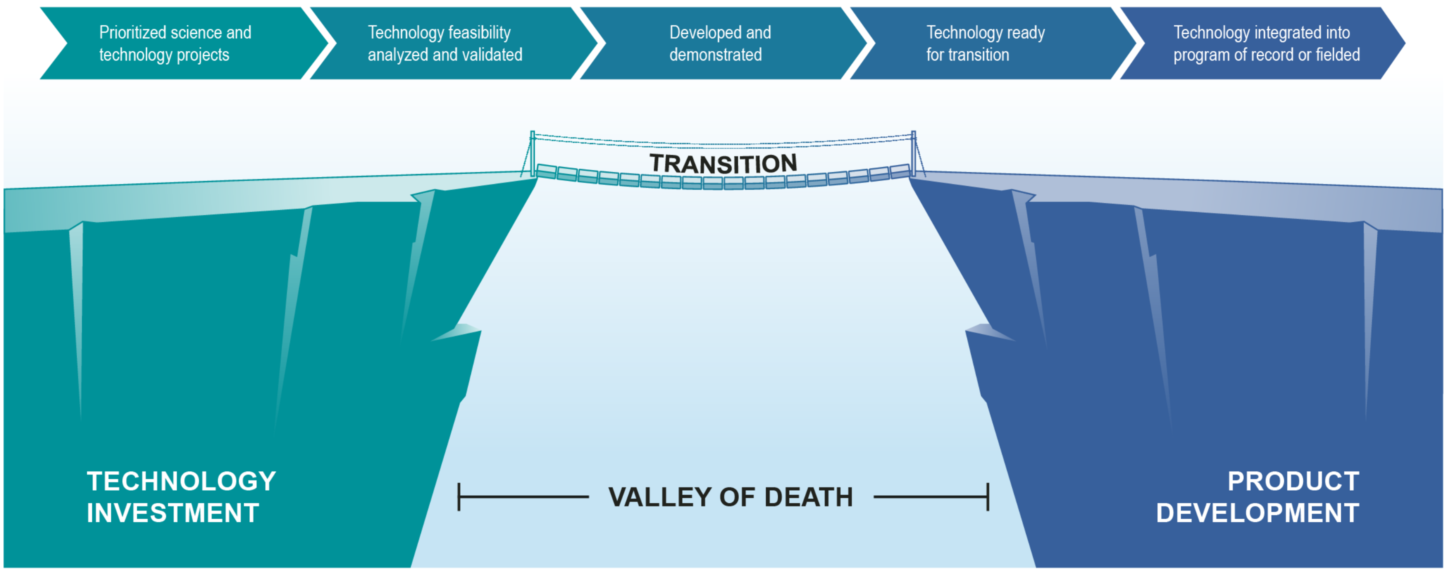
- The technology's potential has not been adequately demonstrated or recognized.
- The military departments may not be willing to budget for funding final stages of development.

Despite the challenges for transitioning technologies, prior DOD and GAO work found that this gap can be bridged through cooperative efforts from both communities. Technology development officials can make decisions that balance needs, resources, and technical feasibility in a way that is responsive to the end-user. Acquisition programs and intended end-users can provide early project endorsement, and communicate measurable performance metrics for the technology to achieve. Overall, this requires early and frequent collaboration among the developer, acquirer, and user.[16] We have found that formal transition agreements and other project assessment measures are important to ensure projects stay on track and stakeholders sustain their commitments.[17] Figure 3 illustrates DOD's technology management and development process and transition vulnerability over the "valley of death."

[16] GAO-16-5.

[17] GAO-13-286.

Figure 3: Department of Defense (DOD) Technology Management Process and Depiction of Transition Vulnerability over the "Valley of Death"



Source: GAO review of DOD information. | GAO-23-105868

DOD and Military Departments Have Undertaken Steps to Coordinate on and Develop Multiple Types of DE Weapons

DOD and the military departments have undertaken several efforts to support the development of DE weapons. This includes taking steps to coordinate, test, and develop processes to support DE technology development, developing and demonstrating DE technologies in operational environments, and initiating an HEL scaling initiative to increase power output of future technologies.

DOD and Military Departments Have Undertaken Steps to Coordinate, Test, and Develop Processes to Support DE Technology Development

DOD and military departments have undertaken several initiatives related to supporting the development of DE weapons. These initiatives include extensive department-wide coordination and planning efforts, testing procedures and technologies, and developing a review process for prototypes to be used in the field.

Coordination and planning. DOD engaged in several coordination and planning efforts, such as creating the Joint DE Transition Office, which oversees multiple department-wide DE technical area working groups.[18] These groups include multiple representatives from the Army, Navy, and Air Force that discuss crosscutting DE technology investments, such as for beam control and tracking.

Additionally, DOD developed the 2021 DOD Directed Energy Roadmap as a way to communicate the department's overall DE goals and help facilitate coordination among the military departments. The Roadmap describes coordinated efforts, goals, initiatives, types of technologies, and department-wide DE-related challenges.

DOD officials and industry representatives described instances of coordination among the military departments with the sharing of effective technologies across DE weapon systems. For example, DE weapon systems within the Army and Air Force share a targeting and tracking system because of demonstrated effectiveness. Additionally, each of the military departments has participated in sharing where prototypes or components developed at one department were used to develop prototypes at another. For example, Army officials said the Air Force developed an HPM that the Army considered pursuing. While the Army did not ultimately pursue that technology, Army officials said that they leveraged that technology in their own prototype development. This coordination means that improvements to the system can be shared across DE weapons.

A number of entities across DOD are involved in identifying requirements for, developing, and testing DE efforts, as listed in table 2.

[18]The Joint DE Transition Office was originally the High Energy Lasers Joint Technology Office and was formed in 2001. Additionally, the William M. (Mac) Thornberry National Defense Authorization Act for Fiscal Year 2021 directed DOD to establish a Directed Energy Working Group to (1) analyze and evaluate the current and planned DE programs of each military department; (2) make recommendations to the Secretary of Defense; (3) identify methods of quickly fielding DE capabilities and programs; and (4) develop a compendium on the effectiveness of DE weapon systems and integrate the compendium into an overall manual. Pub. L. No. 116-283, § 215.

Table 2: Selected DOD Organizations Involved in Directed Energy Efforts

Organization	Organizational component
Army	Space and Missile Defense Command
	Army Test and Evaluation Command
	Rapid Capabilities and Critical Technologies Office
	Armament Research, Development, and Engineering Center
	Joint Counter-small Unmanned Aerial Systems Office
Navy	Naval Sea Systems Command, including: Naval Surface Warfare Center Dahlgren Division, and Program Executive Office – Integrated Warfare Systems
	Office of Naval Research
	Surface Warfare Directorate
Air Force	Air Force Research Laboratory
	Air Force Life Cycle Management Center, including the Digital Directorate
	Air Force Special Operations Command
Other/DOD-wide	Missile Defense Agency
	Directed Energy Joint Transition Office
	Office of the Undersecretary of Defense for Research & Engineering
	Test Resource Management Center
	Director, Operational Test and Evaluation
	Combatant Commands

Source: GAO analysis of Department of Defense (DOD) information. | GAO-23-105868

Testing procedures and technologies. DOD and the military departments planned for and invested in DE weapon testing capabilities. To support the development of infrastructure necessary to test DE efforts, the Test Resource Management Center developed a DE testing roadmap, updated annually with input from more than 75 participants across DOD. The testing roadmap helps to prioritize investments in testing infrastructure, advanced instrumentation, and test targets representative of modern threats. DOD testing officials said that it is important that the appropriate testing infrastructure is in place to determine the effect that DE weapons have on targets. For example, to test HEL, DOD needs testing instrumentation to measure the beam output as well as the magnitude of the effect on the target. To test HPM, DOD is developing instrumentation to measure the susceptibility of various electronic technologies to HPM.

DE weapon review process. To ensure DE weapons that are fielded are adequate, feasible, and acceptable, each prototype undergoes a review process called the DE Weapon Review and Approval Process before fielding.[19] This process requires that a Combatant Commander initiates the use of DE weapons and develops concepts of operations for its use. This review process allows stakeholders to determine, among other things, whether DE weapons will likely perform as intended. Stakeholders include representatives from military departments, the Office of the Secretary of Defense, and Joint Staff. DOD officials said a process like this is typical for new technologies and that, as DE weapons become more widely used and understood, the requirement to conduct these extensive reviews may no longer be necessary.

DOD Has Operationally Demonstrated Multiple DE Weapons Capabilities

DOD has demonstrated multiple DE weapons capabilities, including a range of technologically mature systems and components. Specifically, each of the military departments has developed DE weapons that have been demonstrated in relevant or operational environments, a key developmental event in demonstrating technology maturation. Additionally, DOD matured component technologies that support DE weapons, and each of the military departments developed a range of technologies.

To respond to certain threats, DOD and the military departments have developed multiple types of DE weapons. Over the last decade, this has included demonstrating and prototyping more than 20 DE weapon systems. Most of the HELs developed during this time are in the 10-to-60 kilowatt (kW) class power range. DOD officials told us that this class of laser has been used in live fire demonstrations to successfully disable, or shoot down, uncrewed aerial systems (UAS), also referred to as drones.[20] DOD DE development officials say drones are uniquely challenging because they can be inexpensive enough for adversaries to deploy in large quantities in combat zones; and traditional defensive tools, such as kinetic weapons, are expensive to use against them. These officials also note that countering drones in civilian areas with traditional kinetic kill weapons could pose risks of casualties, because the use of these can involve large explosions and debris. In contrast, DE weapons could be

[19]Chairman of the Joint Chiefs of Staff Manual (CJCSM), *Directed Energy Weapon Initial Operational Employment Review and Approval Process,* 3230.01A (Oct. 7, 2015).

[20]According to the DOD Fiscal Year 2009-2034 Unmanned Systems Integrated Roadmap, DOD classifies UAS into five groups based on weight, operating altitude, and airspeed. Group 1 UAS are the lightest at 0-20 pounds at takeoff, operate at altitudes around 1,000 feet above ground level, and fly at speeds around or below 100 knots. Group 5 UAS can weigh thousands of pounds, operate above 18,000 feet, and have any airspeed. For the purposes of this review, we are using the gender-neutral term uncrewed as a replacement for the term unmanned except when referring to the proper name of a DOD document or program.

useful because they can disable the drone with less risk of collateral damage. Other DE weapons under development have been designed to have improved capability with power ranges up to 300kW. Specifically, HEL in the 300kW class range are designed to respond to targets such as rockets, artillery, and mortars. In addition, the military departments developed a range of HPM capabilities for the purposes of engaging missile or drone swarm attacks against a base. Some details of HPM efforts are classified.

Each of the military departments has made specific contributions to developing DE technologies. This process of developing DE technologies has meant that warfighters have access to this technology to address needs and allow for learning in an operational environment.

Army. The Army developed a broad range of capabilities, including:

- a 20kW counter-UAS HEL,
- a 50kW HEL to use on a maneuver platform,
- a laboratory tested 300kW HEL, and
- an HPM system.

In addition, the Army has made and plans to continue to make investments into the manufacturing industrial base for DE weapons. Examples of these investments include improving cost and speed of production of critical DE components, such as optics and mirrors. The Army identified several improvements already, including reducing the speed of producing a component from 6 months to 3 months and increasing production of another component from four units to 20 units per week.

Navy. The Navy developed several DE efforts that can be used on ships, including:

- a low kW dazzler to disrupt drones,
- a 150kW laser to counter small boats, and
- several HPMs.

Additionally, to support integration of DE weapons on ships, the Navy is developing energy magazines—an energy storage device—to enable DE weapons with higher power requirements than can be supported by the systems currently installed on some ships on their own.[21] When activated, DE weapon systems and sensors can suddenly increase energy demand from a platform, which could exceed what the onboard generators can produce. These generators are operated at a continuous power level for efficiency and reliability and may not be able to boost output to support a large demand over a short period of time. The Navy's energy magazine is being designed to provide a shipboard-ready power system to support DE weapon, sensor, and electronic warfare power needs during a conflict by providing power during an engagement. The energy magazine is being designed to charge when systems are not in use so that generators can continue to operate efficiently and not be strained by erratic levels of high demand. In addition, the Navy's energy magazine will be designed to be scaled to meet power requirements and supplement ship generators. This would give the Navy the ability to make existing vessels capable of using future DE weapons and sensors.

Air Force. The Air Force developed a range of DE capabilities that could potentially be used in either air or land, include the following:

- a 50kW HEL system that can be mounted to tactical aircraft,
- a 10kW HEL system integrated with a light ground vehicle,
- a counter-UAS HPM system, and
- several other HPM efforts.

In addition to developing DE weapons, the Air Force has invested in technologies to address specific DE-related challenges. For example, flight at high speeds generates vibrations that requires DE weapon designs to be ruggedized to a flight environment. In addition, the typical turbulence caused by airflow moving around the aircraft or a DE weapons system at high speeds—including supersonic speeds—would make it difficult to use HEL weapons, because the beam could get distorted or disrupted by this turbulence. The Air Force invested in developing technology to reduce turbulence affecting these DE systems. This investment and development may support the Air Force's effort to mount HEL onto aircraft moving at high speeds and maneuvering. The Air Force also sponsored an experimentation campaign from 2020 through 2022 that used modeling and simulations and war-gaming exercises.

[21]An energy magazine refers to a system used to store energy for later use by a weapons system. Such a system is used to support sustained engagement and, ideally, would allow for infinite use as long as fuel is available.

DOD and the military departments are also investing in component technologies that improve DE weapon capability. These include the following:

- Identifying more effective aimpoints for potential DE weapon targets. Each military department conducts vulnerability assessments for various threats, which are coordinated by the Joint DE Technology Office. These assessments are used to develop target descriptions and support a DOD initiative to build a database of those targets to help inform the best way for a DE weapon to defeat them.
- Using adaptive optics to improve beam quality—the measure of how well a beam can be focused—so that systems remain effective over distance.

Additionally, the military departments are also integrating DE weapons into command and control systems. Improved integration means DE weapons will have real-time information on incoming threats, which enables DE weapons like HEL to quickly identify and track precise aimpoints.

DOD Is Pursuing Higher Power Weapons for Improved Capabilities

DOD, in coordination with each of the military departments, is pursuing higher power laser weapons for improved capability to engage a broader range of threats. In 2019, DOD introduced the High Energy Laser Scaling Initiative to leverage current technologies, increase the power output of HEL, and expand the potential range of HEL mission sets. The Office of the Under Secretary for Research and Engineering leads the initiative, which includes three HEL development efforts. DOD and each of the military departments are working toward building lasers with output in the 300-, 500-, and 1,000kW power ranges. Such systems could eventually enable HEL to engage powerful targets such as cruise missiles. According to DOD, the initiative supports the improvement of directed energy weapon capability by focusing on increasing output power, refining energy delivery to targets, and developing efficient power and laser generation systems.

In addition, the initiative aims to develop the industrial base so that the military departments can make additional purchases of HEL at 300kW and above. As part of this initiative, DOD is supporting three different technology development approaches. DOD officials said they expect the laser scaling initiative to result in an HEL prototype in the 300kW class delivered in fiscal year 2023. After delivery and integration of the HEL prototypes and testbeds, DOD officials said that the weapon systems may participate in counter-cruise missile demonstrations and exercises.

While a DOD official confirmed DOD does not have a similar coordinated effort to develop higher power HPMs, some military departments continue to invest in more powerful HPM systems for greater capability, including higher power and increased range.

Two Military Departments Have Not Consistently Taken Steps to Support DE Technology Transition

The Army, Navy, and Air Force reported in budget requests that they expect to transition selected DE prototypes to acquisition programs when the technology is ready. The Army has taken actions that provide a foundation to transition DE technologies that meet the Army's warfighter and acquisition community needs. However, the Navy and Air Force have not consistently applied prototype transition practices, such as identifying transition partners early, drafting transition agreements, and documenting their user feedback process.

DE Weapons Technology Faces Barriers to Transition

For prototypes that are expected to transition to an acquisition program, the unique nature of DE weapons technology may present novel variations to the traditional barriers to transition.[22] DOD officials pointed out that, DE technology is fundamentally different than the kinetic weapons the military departments are accustomed to using. Therefore, not having long-term experience with them limits the understanding of how to integrate DE weapons into missions which may, in turn, make obtaining "buy-in" from potential users more challenging.

Near-term challenges with transitioning DE technologies beyond the development stage include space, weight, and power; testing; and meeting the defense industrial base needs.

Space, weight, and power. DE weapons require integration into existing platforms such as vehicles, ships, and aircraft. This integration may be as simple as plugging into a radar, or as challenging as removing and repurposing sections of a Navy ship. Further, DE weapons require power that may be integrated into the weapon or may need to be provided directly from the platform. HEL also generate heat that must be managed. A cooling mechanism to absorb or transfer this heat may take up significant space. These system requirements may pose challenges on platforms with limited space and power, such as ground vehicles or

[22]As discussed earlier, prototypes can result in a variety of outcomes, including transitioning for further development or into acquisition programs, or termination. For the purposes of this discussion, we are focusing on only those DE efforts that have been identified by the services for transition into an acquisition program, and therefore potential transition partners include weapon system programs or DOD components.

aircraft. Specifically, DOD officials said some HEL weapons have about a 25 to 40 percent efficiency rate, which means that about 25 to 40 percent of power used by the weapon is used in the laser. Some of the rest of the energy is released as heat that must be absorbed or transferred elsewhere, often through some cooling system. Although DOD has experience managing space, weight, and power considerations for new weapons, integrating the specific needs of DE weapons onto platforms requires advanced planning.

Testing limitations. Testing DE weapons to verify and validate performance observed in laboratories can be limited for several reasons, including access to operational environments. For example, testing HEL against airborne targets could inadvertently damage or destroy sensitive components on satellites. Because of this, developers must consult a laser clearing house to determine when it is safe to shoot an HEL weapon above the horizon in a testing, training, or maintenance environment. Unlike testing kinetic weapons, this restriction tightly controls HEL testing and may prohibit an HEL weapon from firing in a test range. This may make it challenging for potential transition to acquisition or fielding because the full capability or limitations of a DE weapon system may not be fully understood ahead of transition.

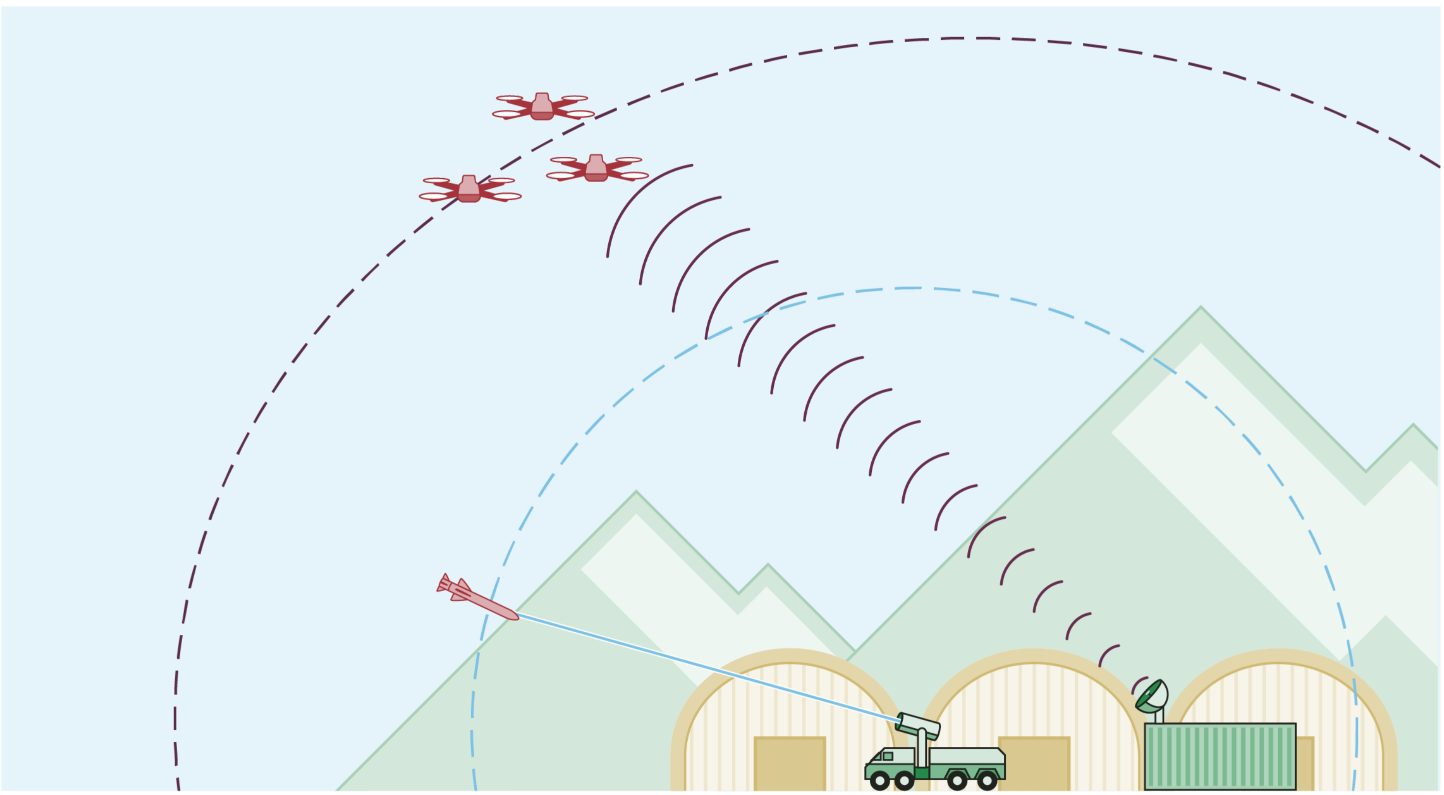
Defense industrial base. Representatives of companies within the defense industrial base have expressed hesitation to invest in developing DE technologies without a government commitment. Unlike other emerging technologies where DOD may leverage commercial products to build military products, there are no current commercial applications for DE weapons or key technologies. As a result, contractor representatives emphasized the need for a clear “demand signal” from DOD about future investments in DE technologies to support internal investments. Officials pointed out that current costs to develop DE weapons are high because of the relatively low number of initial development efforts. Therefore if DE weapons were produced in larger quantities, costs may be spread out over more units, lowering costs per unit.

Longer term, there are challenges with battle management; tactics, techniques, and procedures; maintainability; and user safety concerns.

Battle management. Battle management refers to how commanders at all echelons of conflict make decisions based on available information. Commanders make decisions about weapon selection with the objective of best achieving operational goals. Oftentimes, there is an emphasis on quick decision-making after processing large quantities of information.

Commanders' decisions to use DE weapons will likely require considering the weapons' benefits, such as lower cost, and limitations, such as time on target. Further, compared to kinetic weapons, DE weapons may not have the same range capability. Thus, the decision about whether to use them, and when, may be challenging. Figure 4 shows an example of the way DE weapons may be used as part of a layered defense strategy.

Figure 4: Notional Depiction of Long Range High Power Microwave and Short Range High Energy Laser Used to Defend a Military Installation



High Energy Laser Range

High Power Microwave Range

Source: GAO analysis of Department of Defense information. | GAO-23-105868

Tactics, techniques, and procedures.[23] As a novel technology, DE weapons require the development of new tactics, techniques, and procedures; processes by which the warfighter knows how best to use a particular technology in an operational environment. For traditional kinetic weapon systems like missiles, their use is well understood, and changes to missile systems improve capability but do not require a fundamental change in use. For example, officials said the tactics envisioned for using a DE weapon by the developer may not be how a warfighter would employ the system. Because of this, tactics would need to be reworked for the DE system, with any necessary design changes. The tactics, techniques, and procedures to support use of DE weapons for a broad range of uses are still being developed.

Maintainability. The internal mechanisms for DE weapons are sensitive, and typically require a specialized clean room for repairs. For example, DOD officials said that one DE weapon fielded to an operational environment encountered challenges with battery charge and cooling, and had to be returned to the manufacturer in the United States for repairs. Ultimately, this challenge reduced system availability, which is key to a successful weapon. Developing maintenance and sustainment processes for weapon systems is a key role for an acquisition program office. The ease of maintaining a weapon may factor into an acquisition program office's decision to pursue that technology compared with another.

User safety concerns. Several DOD and military department officials described a possible apprehension among users regarding potential biological effects of DE weapons, such as a fear that personnel might be blinded by a laser. DOD reported undertaking rigorous testing and other measures to ensure safety of personnel, and DOD officials said education among users may help encourage adoption of this new technology.

[23]Tactics are the employment and ordered arrangement of forces in relation to each other. Techniques are non-prescriptive ways or methods used to perform missions, functions, or tasks. Procedures are standard, detailed steps that prescribe how to perform specific tasks.

Navy and Air Force Leadership Have Not Consistently Taken Key Steps to Support Expected Transition to Acquisition Programs

Two military departments reported they expect to transition to acquisition programs when the technology is ready, but have not consistently taken key steps to support transition. Specifically, leaders of two military departments have not consistently taken key steps identified in DOD's prototyping guidance to support transitioning prototypes: the early identification of a transition partner and drafting transition agreements. With the support of leadership, Army engages multiple stakeholders and documents transition plans early in the prototyping process for DE weapons. However, the Navy and Air Force leadership have not consistently identified transition partners or drafted agreements to support transition to acquisition programs once the DE prototype was expected to transition.

Army Leadership Takes Steps to Support Expected Transition of DE Weapons to Acquisition Programs

For prototypes the Army has reported it expects to transition to acquisition programs, Army leadership supported the implementation of the two key steps to support transition: identifying a transition partner and drafting a transition agreement. In 2019, the Army Board of Directors initiated the Army's current approach to developing DE through the Multi-Mission High Energy Laser Technology Maturation Initiative. At that time, the Board directed the Rapid Capabilities and Critical Technologies Office to develop combat-capable DE weapon prototypes as part of modernization efforts for Army Air and Missile Defense.[24] Once successful prototyping has been completed, the Army expects to proceed to a program of record. Program Executive Office (PEO) Missiles and Space will be the office responsible for doing so.

We have found early planning, including establishing military demand and active collaboration with transition partners, as key indicators of successful transition from prototype development to use by the warfighter.[25] Further, the DOD Prototyping Guidebook states that some prototyping efforts will transition into their own acquisition program. If this pathway is expected from the outset of the prototyping project planning, it would be prudent to begin planning and coordinating the transition as early as possible. Specifically, the 2019 DOD Prototyping Guidebook lists drafting a transition agreement between the program manager and the transition partner within the first year of the project as a best practice.

[24]DE weapon prototypes are part of four modernization efforts: (1) Army Air and Missile Defense integrated battle management, (2) Counter Unmanned Aerial Systems, (3) Maneuver – Short Range Air Defense, and (4) Indirect Fire Protection.

[25]GAO-16-5.

DOD's 2022 version of the guidebook notes that a transition partner should be identified and an agreement drafted as soon as possible.[26]

We have previously reported that documented technology transition agreements with technology and business readiness metrics can help transition partners track the progress of new technologies.[27] Additionally, transition planning agreements are not meant to weigh down either the innovators or the potential transition partners. Instead, these agreements are not static and, according to the DOD Prototyping Guidebook, should be regularly revisited by the developer and the transition partner as prototype projects progress.

The Army drafted transition agreements to establish the conditions that enable transition of DE efforts to acquisition programs beginning in fiscal year 2025, when the prototype is ready. To support this effort, Army officials described embedding transition teams in the prototyping effort to monitor technology development progress and relay information to the transition partner, so that the acquisition program office understands the capabilities it is receiving and can provide feedback. As part of the transition agreement, the Army engaged in several planning activities, including budget planning and determining how funding obligations will transition development to the PEO, all in an effort to be ready once the transition decision is made.

The Army developed a detailed plan, called an "octagon," describing schedules and stakeholder roles to build supporting activities around the use of DE weapons. This includes semiannual meetings to coordinate not only development of the prototypes themselves, but to plan for the next steps in using a DE weapon. This includes developing what DOD refers to as DOTMLPF-P, or "doctrine, organization, training, materiel, leadership, personnel, facilities, and policy for DE weapons" to support future use.

[26]Department of Defense, *Department of Defense Prototyping Guidebook,* Version 2.0 (Washington, D.C.: November 2019). This Guidebook has a more recent version, released in October 2022, which includes the best practices identified in Version 2. In 2019, Version 2.0 of this guide stated that: "to increase the likelihood that the project will transition as planned, a transition agreement between the program manager and transition partner should be drafted within the first year of the project and all affected parties should sign the agreement." We refer to this earlier version because the 2022 update, Version 3.0, did not provide specific and measurable time frames for drafting transition agreements.

[27]GAO, *Best Practices: Stronger Practices Needed to Improve DOD Technology Transition Processes,* GAO-06-883 (Washington, D.C.: Sept. 14, 2006).

Additionally, the Army developed early planning documents used to support acquisition programs of record. For example, for one prototype, Army officials described developing an “abbreviated Capabilities Development Document,” a document that specifies requirements for the system that will deliver the capability to meet the performance criteria specified by operational need.

Army officials said that no final decision has been made about whether any current Army prototypes will transition to programs of record. These officials said that they will make that decision based on Army needs, and the ability of the technology to meet those needs. Should the Army decide to pursue a program of record, having these actions in place will help support transition when ready.

Navy Leadership Has Not Taken Key Actions to Support Expected Transition of DE Capability

The Navy reported that it expects to transition several DE technologies to acquisition programs, but has not drafted transition agreements to support the transition of systems we reviewed. The Navy developed DE prototypes to demonstrate DE weapon technical feasibility on ships or in response to urgent operational needs. However, it has not taken a key action identified in the DOD Prototyping Guidebook to draft transition agreements for selected efforts, even though—as indicated in the Navy budget documents—the Navy expects to transition these prototypes.

The Navy reported that it identified potential transition partners for DE weapons. Overseeing transition, the Assistant Secretary of the Navy for Research, Development and Acquisition is responsible for the development and acquisition of Navy platforms and weapon systems. In general, Navy officials said the Navy’s current process for developing and transitioning DE technologies is through a partnership between the Navy science and technology community and the PEO, Integrated Warfare Systems, which supports fielding, testing, and maintaining DE weapon prototypes. This includes working with Navy sailors and vessels to schedule DE weapon installment onto ships, and recording data on DE weapon usage for the development community. In addition to the technology developers and the PEO, the Surface Warfare Directorate supports DE efforts by funding the installation of the weapons onto ships and developing requirements for DE weapons from warfighters and through strategic documents.

The Navy’s strategic documents describe future plans to use DE weapons capable of defeating anti-ship cruise missile threats, but the Navy has not taken a key step to enable the transition of the DE efforts into acquisition programs. Specifically, even with plans for increasing DE power output to meet counter anti-ship cruise missile requirements and demonstrating and fielding additional DE weapon prototypes in the next several fiscal years, the Navy has not documented transition agreements, including funding and requirements to facilitate future transition efforts for prototypes that are expected to transition to acquisition programs. Navy officials said they have identified transition partners and have ongoing discussions with the Surface Warfare Directorate and PEO Integrated Warfare System throughout the development of the effort, but they do not have documented agreements.

Although the Navy reports that selected prototypes are expected to transition to an acquisition program in fiscal year 2024, the Navy has not drafted a transition agreement among the potential transition partners. Navy officials said they are waiting on additional testing to ensure the capability could meet the Navy's needs to defeat anti-ship cruise missile threats before generating agreements between developer and the acquisition community. Navy officials also said that they are undergoing a broader mission analysis through an initiative called the Navplan Implementation Framework to better determine how weapons, including DE weapons, fit into future battle management.

Drafting transition agreements early could better support the Navy's efforts to eventually transition DE technologies when ready. Navy officials reported that current and future Navy ships would not be able to provide the necessary power and cooling to a DE weapon with significant power output. Specifically, the Navy cited several integration challenges that require early planning to address including ventilation, fire suppression, and cooling. Although the Navy has efforts underway to address the power required for future weapon systems, the Navy also reported that the unique power requirements of DE weapons make energy storage a challenge, and that current mission energy demands outpace ship capability, even without factoring in DE needs. Documenting a transition agreement can provide developers with information such as the criteria that need to be met to transition the technology. Without early transition planning and drafting transition agreements, the Navy risks developing technology that is misaligned with operational needs.

Air Force Leadership Has Not Consistently Taken Key Steps to Support Expected Transition of DE Capability

The Air Force reported that it expects to transition DE counter-UAS technologies to acquisition programs, but has not consistently taken key steps to support this transition. Specifically, the Air Force does not consistently take early steps, per DOD's Prototyping Guide, to identify transition partners and draft transition agreements for prototypes it expects to transition to an acquisition program when ready.

Air Force officials reported that technology transition partners typically include the technology developers, the acquisition community, including PEOs, and users in the operational community, such as a major command. The Office of the Assistant Secretary of the Air Force for Acquisition, Technology, and Logistics oversees Air Force research, development, acquisition, and program sustainment activities. In general, the Air Force's current process for developing and transitioning DE weapons is through partnership between the Air Force science and technology community, including the Air Force Research Laboratory (AFRL) and the Air Force major commands, which support fielding, testing, and maintaining DE weapon prototypes. Air Force major commands have sponsored experimentation plans and technology demonstrators executed by AFRL. Additionally, AFRL has funding for early technology and prototype development it leverages for selected technologies.

In one effort we reviewed, the Air Force identified a transition partner and documented requirements agreed upon by developers and the transition partner. This effort was an advanced technology demonstration, or pre-prototyping, airborne laser effort, where officials initiated a technology transition plan between the technology developers and an Air Force major command. In this instance, the technology transition plan included types of technology to be developed, goals, and criteria for continued development efforts. The plan was signed by both developers and a transition partner, and included flexibility to adjust as needed. The plan acknowledged that, given the factors outside of parties' control, the commitment for future funding was not binding. Officials said having this early coordination and agreement helped establish parameters for developing the technology, but acknowledged that some additional information would be necessary for such an effort to move into prototyping. Specifically, officials said that, without knowing whether the Air Force plans to use airborne lasers in a crewed or uncrewed aircraft, developers do not know whether to design a laser mounted to the outside of an aircraft, such as in a pod affixed to the body of the aircraft, or integrated with the aircraft itself.

For other efforts the Air Force expects to transition to acquisition programs, though the Air Force has not taken key steps to support transition. Specifically, one counter-UAS HEL prototype we reviewed was under development and testing for more than 3 years—with the expectation of transitioning into an acquisition program when ready—before a transition partner was identified. Air Force officials said that it was unclear who the transition partner should be, even though a transition partner, PEO Digital, was identified in 2021. However, the prototype did not fully align to program office needs, and the office did not have funding planned—nor transition agreements in place—to support initiating a DE weapon acquisition. Officials from PEO Digital, the identified transition partner, said that DE is one of a large number of technologies they are considering to meet their counter-UAS mission.

The future of DE weapons in the Air Force is unclear. Although the Air Force developed a number of technologies that have been leveraged across DOD, Air Force leadership has not incorporated DE efforts into funding planning over the next few years, and there are no current agreements to transition any DE efforts. Over the long term, the Air Force has expressed interest in using DE weapons but has not consistently taken key steps to support transition. Air Force officials said work is still underway to understand the technological maturity DE weapons need to achieve, as well as the way to effectively apply DE weapons during a conflict. Further, officials cite ongoing technical challenges when considering how DE weapons fit into Air Force mission needs. Without identifying transition partners early and drafting transition agreements, the Air Force risks developing technology that is misaligned with operational needs.

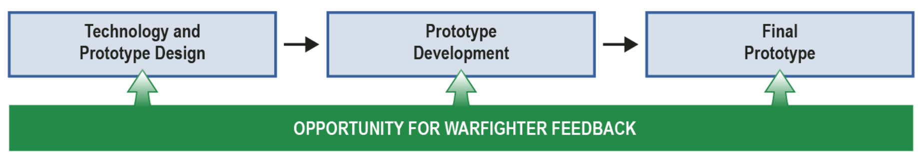
Navy and Air Force Do Not Consistently Document How They Collect, Track, and Incorporate Feedback

Each of the military departments report soliciting user feedback throughout the design and development of demonstrators and prototypes. The Army also has detailed tracking mechanisms to gauge the types and amount of feedback received, and how it is incorporated. However, the Air Force and Navy do not have a formal process for collecting, tracking, and incorporating feedback during the design and prototyping phases of DE development.

Officials from each military department described collecting feedback from warfighters in a variety of ways, including informal discussions, allowing warfighters to test prototypes, modeling and simulation exercises, and ongoing discussions with operators using prototypes in the field. Each military department reported receiving helpful feedback, such as on equipment user interfaces. Specifically, each military department reported receiving feedback that helped it leverage a video game controller-like interface to make operating DE weapons more intuitive to warfighters. Warfighters also gave practical feedback, including that operators may be eating while using the DE weapon, so having a touch screen is problematic.

GAO's leading practices for product development, including prototyping, emphasize the importance of collecting customer feedback to inform improvements or to identify challenges that need to be addressed.[28] DOD best practices recognize end-user involvement as a best practice for evaluating prototypes. Figure 5 shows that feedback can be incorporated at multiple points throughout the development of prototypes.

Figure 5: Opportunities for Warfighter Feedback throughout Prototype Development



Source: GAO analysis of Department of Defense information. | GAO-23-105868

Army Tracks How User Feedback Is Collected and Incorporated

The Army documents how user feedback for DE development efforts is collected and incorporated throughout the development process through recorded "soldier touch points" (STP) that represent the number of hours a system has been used by soldiers. This includes incorporating feedback throughout the design and development of a prototype, which helps to ensure feedback is gathered and incorporated early in the process in a variety of areas. For one system we reviewed, Army officials said they documented thousands of STP hours and tracked the number of hours spent on specific aspects and focus areas of development. For example, for one system, Army recorded 179 STP hours focused on developing training tools, 16 STP hours on software development focused on

[28]GAO, *Leading Practices: Agency Acquisition Policies Could Better Implement Key Product Development Principles,* GAO-22-104513 (Washington, D.C.: Mar. 10, 2022). Our prior work has demonstrated that, while structural differences between the private sector and government can affect outcomes, key principles from the private sector can be thoughtfully applied to government acquisition to improve outcomes, even with the different cultures and incentives.

command and control, and 40 STP hours focused on design reviews. Overall, for this system alone, Army reported more than 6,200 STP hours.

The Army also tracks the number of comments received and whether they have been incorporated into design. Army officials reported that this process resulted in improvements to its DE technologies under development. In some cases, users identified design defects that expert designers overlooked. For example, in one instance, development officials reported receiving feedback from a soldier about the design for a laser mounted to a vehicle. Officials said that developers originally positioned the laser to fire through what would be the likely pathway of the vehicle's exhaust. This would have created an atmospheric effect that might have distorted the laser's beam, rendering it significantly less effective. Development officials said this design problem had been overlooked by the developers, and they were able to integrate the feedback into the design, positioning the laser through another path. Officials said making this change at design would help them avoid costs associated with redesign had the issue been identified later.

Navy and Air Force Do Not Consistently Document How They Collect, Track, and Incorporate User Feedback

Navy officials described receiving operator feedback on prototypes but did not formally document the way they collect, track, and incorporate user feedback. The Navy described ongoing efforts to collect regular informal feedback from prototype operators that was incorporated into design modifications. For example, Navy officials described one DE weapon includes eight prototypes that have been installed and used in operational environments over the course of 2 years, starting in 2020. During this time, officials report that operators provided regular feedback that has been incorporated as the prototypes were finalized and installed. Operators we spoke with said that they received a great deal of support from the DE weapon developers, and that they typically do not experience such close support and contact from developers of new technology. However, Navy officials reported that, although they collect and incorporate feedback into prototype designs, they do not specifically document the feedback from operators because they said it wasn't necessary. The informal nature of collecting and using feedback means that there may not be a standard approach that ensures the same level of effort will be used on future DE technology development.

Air Force officials described inconsistent processes for collecting feedback, and an instance where feedback was not incorporated into technology design. Air Force officials described one formal effort to collect feedback, a semiannual modeling and simulation exercise that focused on specific scenarios. Goals of this exercise include improved understanding of HEL capabilities and exposing warfighter to DE capabilities. However, some efforts to collect information are not as formal. For one of the Air Force DE weapons we reviewed, there was no transition partner identified until well into prototype development. Because there was no transition partner to identify intended end-users that could give feedback on their needs, officials described informal efforts to get feedback from available warfighters. These efforts included looking to "see who was around" to have them test out the demonstrators or prototype. This ad hoc approach risks gathering feedback from warfighters that may not be reflective of the needs of ultimate end-users.

Further, Air Force officials described a program where feedback collected early in technology design and development was not incorporated into the design of the DE prototype. Specifically, program officials described collecting user feedback from pilots during the design phase of an airborne HEL technology demonstrator. Officials said that, during this simulation of airborne lasers, pilots reported positive feedback on features of the design and capability. For example, the magazine depth meant they did not have to stop to reload the weapons. However, DOD officials also reported that pilots expressed concerns about the need to fly low and steady while using the laser, which made them more vulnerable. Air Force officials said that, although they understood the concern, they did not factor that feedback into design because the transition partner, the Air Force Air Combat Command, had already provided design requirements for the demonstrator. Officials explained that the effort was a technology demonstration and that the program was planning a fiscal year 2024 flight test.[29] However, because the Air Force does not consistently document how it collects, tracks, and incorporates feedback on design efforts, the military department risks developing DE designs that do not meet the needs of the ultimate end-user.

Conclusions

DOD has long pursued DE weapons but could do more to facilitate the transition of these efforts. DE could provide considerable advantages to the warfighter to address challenging threats, and DOD has invested significant time and resources into developing prototypes. However, the Air Force and Navy have not taken certain steps that could support transition. Specifically, the Air Force does not consistently identify transition partners, and neither the Air Force nor the Navy documents transition agreements to support the transition of DE technologies. Having

[29]The Air Force subsequently decided not to proceed with the flight demonstration and ended development due to cost increases and other technology challenges.

documented transition agreements with partners helps align technology development with warfighter needs, which ultimately helps ensure DE weapons are developed to meet warfighter needs. Additionally, the Navy and the Air Force do not consistently document how they collect, track, and incorporate user feedback into prototype efforts. Consistently documenting how they collect, track, and incorporate feedback into prototype design and development will better ensure significant issues, such as those that affect how a DE weapon can be used on a mission, are addressed early to align with warfighter needs, and support future DE weapon transition efforts.

Recommendations for Executive Action

We are making a total of four recommendations, including two to the Navy and two to the Air Force. Specifically:

The Secretary of the Navy should ensure the Assistant Secretary of the Navy for Research, Development and Acquisition, for efforts the Navy expects to transition to an acquisition program, develop transition agreements between prototype developers and identified transition partners within the first year of a DE prototype project, or as soon as possible. (Recommendation 1)

The Secretary of the Air Force should ensure the Assistant Secretary of the Air Force for Acquisition, Technology, and Logistics, for efforts the Air Force expects to transition to an acquisition program, identify transition partners early and develop transition agreements between prototype developers and identified transition partners within the first year of a DE prototype project, or as soon as possible. (Recommendation 2)

The Secretary of the Navy should ensure the Assistant Secretary of the Navy for Research, Development and Acquisition documents how the Navy collects, tracks, and incorporates DE prototype user feedback during development and testing. (Recommendation 3)

The Secretary of the Air Force should ensure the Assistant Secretary of the Air Force for Acquisition, Technology, and Logistics documents how the Air Force collects, tracks, and incorporates DE prototype user feedback during development and testing. (Recommendation 4)

Agency Comments and Our Evaluation

We provided a draft of this report to DOD in February 2023 for review and comment. DOD provided written comments in March 2023 that we reproduced in appendix II and summarized below. DOD concurred with three recommendations and partially concurred with one recommendation.

DOD concurred with our second, third, and fourth recommendations. DOD partially concurred with our first recommendation to the Navy to develop transition agreements between prototype developers and identified transition partners. While the comments indicate that DOD partially concurred, the comments did not clearly state what aspects of our recommendation they did not concur with. Rather, they noted that the Navy has some degree of coordination built into the way they have organized their directed energy efforts.

We acknowledge that the way the Navy has organized development of DE weapons has facilitated collaboration among developers and transition partners within PEO Integrated Warfare Systems. However, to support eventual transition to an acquisition program when technology is ready, the Navy can better articulate a pathway by documenting plans with key decision makers such as the Surface Warfare Directorate, including the ways that the transition partners plan to identify requirements and transition funding responsibilities.

We are sending copies of this report to the appropriate congressional committees, the Secretary of Defense, the Under Secretary of Defense for Research and Development, the Secretary of the Army, the Secretary of the Air Force, and the Secretary of the Navy. In addition, the report is available at no charge on the GAO website at https://www.gao.gov.

If you or your staff have any questions about this report, please contact me at (202) 512-4841 or ludwigsonj@gao.gov. Contact points for our Offices of Congressional Relations and Public Affairs may be found on the last page of this report. GAO staff who made key contributions to this report are listed in appendix III.

Jon Ludwigson
Director, Contracting and National Security Acquisitions

List of Committees

The Honorable Jack Reed
Chairman
The Honorable Roger Wicker
Ranking Member
Committee on Armed Services
United States Senate

The Honorable Jon Tester
Chair
The Honorable Susan Collins
Ranking Member
Subcommittee on Defense
Committee on Appropriations
United States Senate

The Honorable Mike Rogers
Chairman
The Honorable Adam Smith
Ranking Member
Committee on Armed Services
House of Representatives

The Honorable Ken Calvert
Chair
The Honorable Betty McCollum
Ranking Member
Subcommittee on Defense
Committee on Appropriations
House of Representatives

Appendix I: Objectives, Scope, and Methodology

This report (1) describes the status of Department of Defense (DOD) and military department Directed Energy (DE) weapon efforts; and (2) assesses the challenges with transitioning DE efforts from prototyping and actions the military departments have taken to mitigate the challenges.

For this engagement, we reviewed DOD and military departments' DE development efforts, as described in DOD's 2021 Directed Energy Roadmap. To understand the status of DOD and the Army, Navy, and Air Force's (military departments) DE weapons development efforts, we reviewed DE planning documents, such as the Roadmap and budget documents for fiscal years 2021 and 2022. We used the Roadmap to identify current and planned DE efforts, the status of development, and responsible military departments. We reviewed program briefs for DE efforts within each military department as well as DOD policy on the operational deployment of DE weapons. We also interviewed officials responsible for creating and overseeing the policy.

We interviewed relevant officials from the military departments responsible for the development and fielding of DE weapons. We also interviewed officials responsible for fielding and requirements in the Marine Corps; however, because the Marine Corps does not have independent development efforts, we did not include them in this review. In addition, we interviewed officials from DOD components, such as the Office of the Under Secretary of Defense for Research and Engineering; the Office of the Under Secretary of Defense for Acquisition and Sustainment; Director, Operational Test and Evaluation's Center for Counter Measures; and the Test Resource Management Center. Other DOD agencies, such as the Missile Defense Agency and the Defense Advanced Research Agency, have some DE-related science and technology development efforts. However, we did not include those efforts in our review because DOD reported they are nascent, or the efforts and funding are being moved to other DOD entities.

We conducted site visits to military department installations and contractors responsible for developing DE weapons. Specifically, we met with science and technology, program, and other relevant officials from each military department. In addition, we toured laboratories and viewed prototypes in Virginia for the Navy, in New Mexico for the Air Force, and Alabama for the Army. We also toured White Sands Missile Range to discuss DE testing efforts in an operational testing environment. Finally, we observed a DE weapon prototype installed on a U.S. Navy ship and spoke with operators to better understand issues related to training on, operating, and maintaining the device. We met multiple contractor representatives and toured facilities doing DE development, including both prime and subcontractors, and large and small contractors.

To evaluate challenges associated with transitioning DE efforts, we selected a non-generalizable sample of seven total DE efforts. The selection included efforts from each military department, and both HEL and HPM efforts. Additional selection criteria included the type of technology, such as power levels and the intended use environment. For these selected efforts, we reviewed, if available, transition plans and other documentation describing schedules, funding, and development activities. We then interviewed military department officials responsible for the efforts to gain an understanding of transition plans, and any challenges encountered. We also interviewed the acquisition program office and resource sponsor officials to gain an understanding of transition challenges and the efforts underway to address those challenges. We identified several challenges associated with transitioning DE efforts.

To assess the extent of the challenges, we evaluated the military departments' transition planning for the selected DE efforts based on the DOD Prototyping Guidance from 2019 and 2022 and our prior work on technology transition.[1] We also reviewed documentation and interviewed military department officials to understand the process for soliciting and incorporating warfighter feedback into DE weapon development.

We conducted this performance audit from February 2022 to April 2023 in accordance with generally accepted government auditing standards. Those standards require that we plan and perform the audit to obtain sufficient, appropriate evidence to provide reasonable basis for our findings and conclusions based on our audit objectives. We believe that the evidence obtained provides a reasonable basis for our findings and conclusions based on our audit objectives.

[1]GAO-16-5

Appendix II: Comments from the Department of Defense

OFFICE OF THE ASSISTANT SECRETARY OF DEFENSE
3600 DEFENSE PENTAGON
WASHINGTON, DC 20301-3600

ACQUISITION

MAR 2 9 2023

Mr. Jon Ludwigson
Director, Contracting and National Security Acquisitions
U.S. Government Accountability Office
441 G Street, NW
Washington, DC 20548

Dear Mr. Ludwigson,

This is the Department of Defense (DoD) response to the GAO Draft Report GAO-23-105868, "DIRECTED ENERGY WEAPONS: DOD Should Focus on Transition Planning," dated February 22, 2023 (GAO Code 105868). Detailed comments on the report recommendations are enclosed.

Sincerely,

Tanya M. Skeen
Performing the Duties of Assistant Secretary
of Defense for Acquisition

Enclosure(s):
As Stated

GAO DRAFT REPORT DATED FEBRUARY 22, 2023
GAO-23-105868 (GAO CODE 105868)

"DIRECTED ENERGY WEAPONS: DOD Should Focus on Transition Planning"

DEPARTMENT OF DEFENSE COMMENTS
TO THE GAO RECOMMENDATIONS

The Secretary of the Navy should ensure the Assistant Secretary of the Navy for Research, Development and Acquisition, for efforts the Navy, expects to transition to an acquisition program, develop transition agreements between prototype developers and identified transition partners within the first year of a DE prototype project, or as soon as possible. (Recommendation 1)

DoD RESPONSE: Partially Concur: The Department agrees that the DoD Prototyping Guidance states that transition planning should start early, and as appropriate, include the transition partner. We also recognize that the Navy has organized directed energy prototyping efforts differently than the other Services. For the Navy, PEO IWS 2 is both the prototype developer and the transition partner. PEO IWS 2. is the Technology Development (BA-4 R&D) to Program of Record (BA-5 R&D, OPN, O&MN) transition/development office for directed energy and works closely with the Office of Naval Research (S&T R&D).

The Secretary of the Air Force should ensure the Assistant Secretary of the Air Force for Acquisition, Technology, and Logistics, for efforts the Air Force expects to transition to an acquisition program, identify transition partners early and develop transition agreements between prototype developers and identified transition partners within the first year of a DE prototype project, or as soon as possible. (Recommendation 2)

DoD RESPONSE: Concur

The Secretary of the Navy should ensure the Assistant Secretary of the Navy for Research, Development and Acquisition, documents how they collect, track, and incorporate DE prototype user feedback during development and testing. (Recommendation 3)

DoD RESPONSE: Concur

The Secretary of the Air Force should ensure the Assistant Secretary of the Air Force for Acquisition, Technology, and Logistics documents how they collect, track, and incorporate DE prototype user feedback during development and testing. (Recommendation 4)

DoD RESPONSE: Concur

Appendix III: GAO Contacts and Staff Acknowledgments

Contacts

Jon Ludwigson at (202) 512-4841 or ludwigsonj@gao.gov

Staff Acknowledgments

In addition to the contact name above, the following staff members made key contributions to this report: Raj Chitikila (Assistant Director), Mary Diop (Analyst-in-Charge), Rose Brister, Joe Neumeier, Christine Pecora, Andrew Stavisky, Jay Tallon, Alyssa Weir, and Adam Wolfe.

Related GAO Products

Extra Large Unmanned Undersea Vehicle: Navy Needs to Employ Better Management Practices to Ensure Swift Delivery to the Fleet. GAO-22-105974. Washington, D.C.: September 28, 2022.

Uncrewed Maritime Systems: Navy Should Improve Its Approach to Maximize Early Investments. GAO-22-104567. Washington, D.C.: April 7, 2022.

Leading Practices: Agency Acquisition Policies Could Better Implement Key Product Development Principles. GAO-22-104513. Washington, D.C.: March 10, 2022.

Artificial Intelligence: Status of Developing and Acquiring Capabilities for Weapon Systems. GAO-22-104765. Washington, D.C.: February 17, 2022.

Hypersonic Weapons: DOD Should Clarify Roles and Responsibilities to Ensure Coordination across Development Efforts. GAO-21-378. Washington, D.C.: March 22, 2021.

Electromagnetic Spectrum Operations: DOD Needs to Address Governance and Oversight Issues to Help Ensure Superiority. GAO-21-64. Washington, D.C.: December 10, 2020.

Weapon Systems: Prototyping Has Benefitted Acquisition Programs, but More Can Be Done to Support Innovative Initiatives. GAO-17-309. Washington, D.C.: June 27, 2017.

DARPA: Key Factors Drive Transition of Technologies, but Better Training and Data Dissemination Can Increase Success. GAO-16-5. Washington, D.C.: November 18, 2015.

Defense Technology Development: Technology Transition Programs Support Military Users, but Opportunities Exist to Improve Measurement of Outcomes. GAO-13-286. Washington, D.C.: March 7, 2013.

Best Practices: Stronger Practices Needed to Improve DOD Technology Transition Processes. GAO-06-883. Washington, D.C.: September 14, 2006.

Ballistic Missile Defense: Information on Directed Energy Programs for Fiscal Years 1985 through 1993. GAO/NSIAD-93-182. Washington, D.C.: June 25, 1993.

GAO's Mission

The Government Accountability Office, the audit, evaluation, and investigative arm of Congress, exists to support Congress in meeting its constitutional responsibilities and to help improve the performance and accountability of the federal government for the American people. GAO examines the use of public funds; evaluates federal programs and policies; and provides analyses, recommendations, and other assistance to help Congress make informed oversight, policy, and funding decisions. GAO's commitment to good government is reflected in its core values of accountability, integrity, and reliability.

Obtaining Copies of GAO Reports and Testimony

The fastest and easiest way to obtain copies of GAO documents at no cost is through our website. Each weekday afternoon, GAO posts on its website newly released reports, testimony, and correspondence. You can also subscribe to GAO's email updates to receive notification of newly posted products.

Order by Phone

The price of each GAO publication reflects GAO's actual cost of production and distribution and depends on the number of pages in the publication and whether the publication is printed in color or black and white. Pricing and ordering information is posted on GAO's website, https://www.gao.gov/ordering.htm.

Place orders by calling (202) 512-6000, toll free (866) 801-7077, or TDD (202) 512-2537.

Orders may be paid for using American Express, Discover Card, MasterCard, Visa, check, or money order. Call for additional information.

Connect with GAO

Connect with GAO on Facebook, Flickr, Twitter, and YouTube.
Subscribe to our RSS Feeds or Email Updates. Listen to our Podcasts.
Visit GAO on the web at https://www.gao.gov.

To Report Fraud, Waste, and Abuse in Federal Programs

Contact FraudNet:

Website: https://www.gao.gov/about/what-gao-does/fraudnet

Automated answering system: (800) 424-5454 or (202) 512-7700

Congressional Relations

A. Nicole Clowers, Managing Director, ClowersA@gao.gov, (202) 512-4400, U.S. Government Accountability Office, 441 G Street NW, Room 7125, Washington, DC 20548

Public Affairs

Chuck Young, Managing Director, youngc1@gao.gov, (202) 512-4800
U.S. Government Accountability Office, 441 G Street NW, Room 7149
Washington, DC 20548

Strategic Planning and External Liaison

Stephen J. Sanford, Managing Director, spel@gao.gov, (202) 512-4707
U.S. Government Accountability Office, 441 G Street NW, Room 7814,
Washington, DC 20548