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HYPERSONIC AND DIRECTED ENERGY WEAPONS: EMERGING CAPABILITIES NECESSARY FOR COMPETITION AND CONTAINMENT

INDUSTRY STUDY GROUP PAPER

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EXECUTIVE SUMMARY

Current global conflicts demonstrate significant revolutions in modern warfare; namely, the increasing cost to defend against small, affordable systems and the benefit to strike targets undetected and at will. The U.S. is attempting to address these changes by investing in the critical technologies of hypersonic and directed energy weapons. But after nearly a decade of prototyping and testing—efforts that cost billions of dollars—the U.S. has yet to field a single, sustainable hypersonic or directed energy weapon. The Department of Defense must therefore develop a cohesive strategic plan to advance its hypersonic and directed energy weapon initiatives effectively.

The Department's current requirements for these systems are undefined, a problem resulting in continued development cycles and non-existent production lines. Additionally, the lack of coordination with allies and partners underutilizes their products, resources, and industry. Promptly procuring a limited number of operational hypersonic and directed energy weapons will return the U.S. to its leading technical role that will generate tangible benefits for political, military, and industry stakeholders. To procure credible hypersonic and directed energy weapons expeditiously, the Department should create central authorities for hypersonic development and procurement and prioritize directed energy partnerships.

Hypersonics and directed energy weapons emerged from the current, complex strategic environment, generating implications for policymakers, service members, the defense industrial base, and U.S. allies and partners. Emerging technologies continuously transform the character of war, with hypersonic and directed energy weapons at the forefront of this evolution. Peer adversaries have developed and fielded hypersonic capabilities, posing significant challenges to the U.S.'s technological supremacy in current and future conflicts. Moreover, the ongoing

conflicts in Ukraine and Israel highlight the economic disparity involved when low-cost unmanned aerial vehicles are targeted with expensive kinetic interceptors, illustrating the financial and tactical implications of modern warfare. Strengthening deterrence across Europe and within the Indo-Pacific are national and global security priorities, as are competing with China and containing Russia. These objectives will benefit from hypersonic and directed energy capabilities, but critics remain concerned over the cost, feasibility, and utility of investing in these emerging technologies.

"We will not leave our future vulnerable to the whims of those who do not share our vision for a world that is free, open, prosperous, and secure,"
President Biden.[1]

I. An Inflection Point

On April 13, 2024, Iran launched an astonishing attack against Israeli military installations, firing more than 170 drones, 120 ballistic missiles, and 30 cruise missiles. The result, however, was an incredible display of defense. A multinational shield from Israel, the U.S., the United Kingdom (U.K.), France, Jordan, Saudi Arabia, and the United Arab Emirates intercepted 99 percent of all incoming ordnance.[2] Israel reported no casualties and sustained only minor damage. The price of Iran's attack was $80 to $100 million, but it cost Israel and its allies $1 billion to repel.[3] The defensive result is remarkable, but the economics are more telling: the U.S. and its allies cannot afford to defend against future, sustained autonomous attacks using conventional high-cost munitions.

Less than a week later, Israel retaliated with a new long-range, precise, and survivable missile. The missile struck Iran's coveted S-300 surface-to-air missile system that protected the Natanz nuclear facility.[4] This strike demonstrated something profound and sent a clear signal: Israel possesses the capability to strike any location within Iran without warning, detection, or interception. Iran played down the strike and deescalated tensions. Israel accomplished deterrence.

The recent Iran-Israel engagement unmasked significant evolutions in modern warfare: the increasing cost to defend against autonomous systems and the benefit of penetration at will. The U.S. has addressed these transformations through critical technologies; namely, hypersonic weapons and directed energy weapons (DEW). But after nearly a decade of prototyping and testing—efforts that cost billions of dollars—the U.S. has yet to field a sustainable hypersonic or

DEW. The Department of Defense (DOD) must therefore develop a cohesive strategic plan to advance its hypersonic and DEW initiatives effectively. Currently, DOD's requirements for these systems are undefined, resulting in continued development cycles and non-existent production lines. Additionally, the lack of coordination with allies and partners underutilizes their products, resources, and industries. Promptly procuring a limited number of operational hypersonics and DEWs will return the U.S. to its leading technological position that will generate tangible benefits for political, military, and industry stakeholders. To procure credible hypersonics and DEWs expeditiously, the DOD should: (1) create central authorities for hypersonic development and procurement and (2) prioritize directed energy partnerships.

This paper, the culmination of six months of study and research, will provide background information concerning the threats driving U.S. investments into these technologies followed by two case studies that discuss and diagnose the benefits and challenges of fielding each type of weapon system. It will then conclude with policy recommendations DOD should consider to guarantee the U.S. has the right tools at the right scope for the current strategic environment, an environment characterized by great power competition and the need to contain immediate threats to the free and open international system.

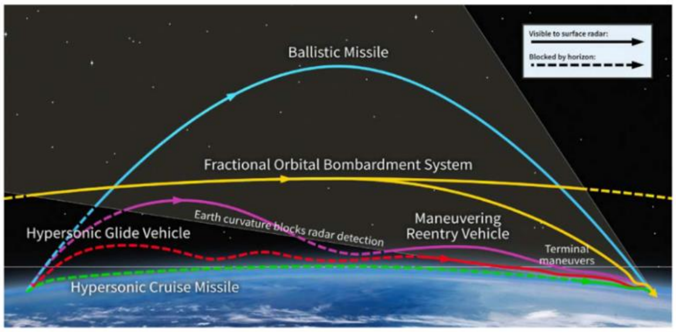
II. The Current Strategic Environment

A. The Current Operating Environment

Hypersonics and DEWs have emerged from within a complex strategic environment that contains implications for policymakers, service members, industry, and U.S. allies and partners. The 2022 National Security Strategy outlines the U.S. faces two peer adversaries in Russia and China, countries whose advanced weapons currently surpass those of the U.S.[5] As a result, Congress has invested crucial defense dollars to maintain the edge or, in some cases, catch up to

Russia and China. Strengthening deterrence across Europe and within the Indo-Pacific are national and global security priorities, as are competing with China and containing Russia. These objectives will benefit from hypersonic and directed energy capabilities, but certain critics remain rightfully concerned over the cost, feasibility, and utility of investing in these technologies.[6]

Despite concerns, hypersonic and directed energy technologies remain U.S. national security priorities. These technologies represent 2 of 14 critical technologies enumerated by the Undersecretary of Defense for Research and Engineering as "vital [for] maintaining the United States national security."[7] Hypersonic[8] missiles travel faster than Mach 5, follow non-ballistic trajectories, and can maneuver in flight (see Figure 1[9]). These characteristics make hypersonics ideal for enemy anti-area access denial (A2AD) systems and targeting power projection assets such as aircraft carriers or foreign basing locations. Because of these attributes, Russia and China have invested heavily in hypersonic missiles, deploying three operational variants, while the U.S. has yet to officially field a system. This gap led the former Chairman of the Joint Chiefs to conclude China's 2021 successful hypersonic missile test served as a "Sputnik moment" for U.S. national security professionals.[10]



[Figure 1: Ground-Based Detection of Hypersonic v. Ballistic Missiles]

Politically, Washington views hypersonic capabilities as a symbol of strength. Congress further recognizes the message sent by the lack of U.S. operational hypersonic weapons in comparison to its adversaries' advancements.[11] Furthermore, allies, such as the U.K. and Australia, seek to develop or purchase hypersonic weapons and other emerging technologies in partnership with the U.S., for example, through the Trilateral Security Partnership Between Australia, U.K., and the U.S. (referred to as "AUKUS").[12]

From the Pentagon's standpoint, hypersonics are an indefensible weapon. A former Vice Chairman summarized hypersonics as "responsive, long-range, strike options against distant, defended, and/or time-critical threats when other forces are unavailable, denied access, or not preferred.[13] A former Obama Administration official was more blunt, describing hypersonics as "instant leader-killers."[14] From an economic perspective, hypersonics are expensive, forcing industry to absorb significant risk without a persistent demand signal. Firms are rightfully wary of this situation, being told to develop hypersonics rapidly, but then facing ambiguous funding streams.

DEWs possess other desirable characteristics. As witnessed in Ukraine and the Middle East, the proliferation of inexpensive drones presents a changing characteristic of war. For example, since October 19, 2023, Houthi rebels have launched hundreds of drone and missile attacks—a near daily occurrence—on Western shipping in the Red Sea, which the U.S. has primarily defended against with multi-million-dollar missiles.[15]

From a military and economic perspective, the U.S. and its allies and partners are concerned with the growing threat drones pose to security and defense. DEWs, including high-energy lasers (HEL) and high-power microwaves (HPM), offer low-cost, enduring solutions. At dollars per salvo, these weapons target incoming projectiles or drones with lasered accuracy or provide a field of disabling microwaves. Technology, and the industrial base, plays a significant role in developing hypersonics and DEWs; therefore, understanding the forces within these markets is vital for Congress and DOD to field these systems successfully and promptly.

B. The Current Competitive Environment

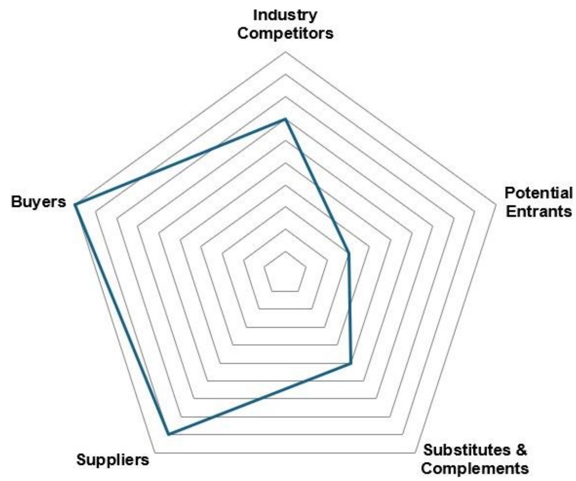
Estimates of the 2024 U.S. defense market indicate it is larger than $309 billion and will grow at a compounded annual rate of 3.58 percent.[16] This market is then expected to expand to $367 billion by 2029.[17] Our two case studies focus on the more-narrow markets of hypersonics and DEWs. Because these critical technologies are identified in the 2023 National Defense Science and Technology Strategy,[18] they will likely receive continued funding into the foreseeable future.

As hypersonics and DEWs garner more attention, understanding their competitive operating environments can assist Congress and DOD in anticipating shifts in competition, shaping how industry structure evolves, and finding better strategic positions and budget opportunities within industry. Using Professor Michael Porter's Five Forces (P5F) analysis, the forces that determine the competitive intensity of a market are: (1) the bargaining power of buyers; (2) the bargaining power of suppliers; (3) the threat of new entrants; (4) the threat of substitute products or services; and (5) rivalry among existing competitors.[19] Important forces will be discussed in turn.

1. Five Forces of Hypersonics

Although narrow, the hypersonic market is large and contains overlapping commercial and military elements. The U.S. has invested billions into hypersonic research, development, testing, and evaluation (RDT&E) since 2000, including $3.8 billion in fiscal year 2022 (FY22) and $4.7 billion in FY23.[20] While the FY24 budget included $11 billion in long-range fires, which includes hypersonics, it did not delineate the hypersonic total.

Considered within this P5F analysis are the two main types of hypersonics: hypersonic glide bodies and scramjet-powered hypersonic munitions. Starting with industry competitors, there are limited firms in this advanced and technical industry. Even the large U.S. defense firms (referred to as the "Big Five" or "Primes') are hesitant to enter alone as most have partnered with other Primes or tier 1 sub primes. This technology is challenging to mature to the tolerances previously expected from the munition industry.



[Figure 2: P5F Hypersonics]

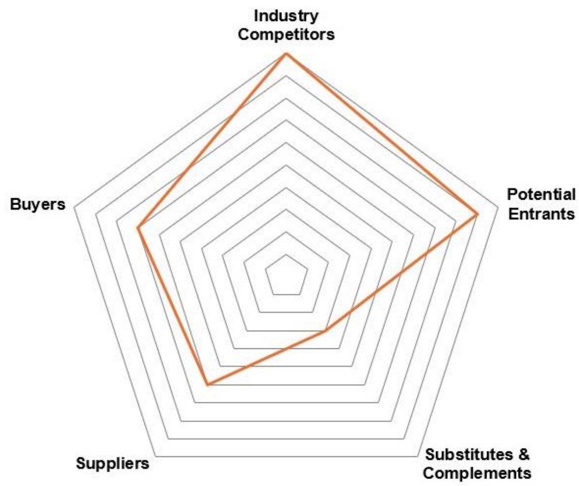
Considering potential entrants, new firms require more capital for RDT&E and low-rate initial production of multi-million-dollar missiles. The few new entrants into this market have been supplemental component participants like the rocket engine. This force is a low threat for substitutes and complements because current munitions do not meet the technical or political requirements for hypersonics.

The suppliers, in contrast, are a considerable force. Highly specialized materials are frequently identified as long-lead or critical because the current list of materials that can withstand a hypersonic environment is small. The materials that can survive are often in short supply or take months to produce. Finally, the buyers of hypersonic systems are the most critical force. Currently, the sole buyer is the U.S. government. This sole buyer must, therefore, deliver a strong and consistent demand signal if it wants hypersonic programs to consist of more than "one and done" missiles.

2. Five Forces of Directed Energy

DOD requested approximately $1 billion for DEWs in FY24.[21] This analysis will focus on two types of DEWs: HELs and HPMs. The spectrum of the DEW market spans from mature technical readiness level (TRL) projects being field tested overseas by the largest defense contractor to some of the smallest companies simply attempting to gain market access.[22]

Within a P5F framework, industry competitors evaluate the number of existing rivalries. This category is fully represented by the "Big Five,"[23] multiple mid-tier companies, and several venture capital start-ups. A P5F analysis indicates this force is intense. While HELs are not new, the system integration and size, weight, and power (SWaP) limitations on usable platforms are difficult.



[Figure 3: P5F Directed Energy]

In comparison, this market has a low threshold for entry. Novel concepts are either gaining enough traction to receive funding or being bought by the Primes, who are looking for a market advantage. Because of the currently available technology, the substitutes and compliments for HELs and HPMs are a lower threat. Similar to hypersonics, the supply chain suppliers constrain crucial components and refined elements. Their force is high.

HEL and HPM systems are government-owned and operated. Governments are the only buyers, and this is currently limited to the U.S. and its allies and partners. There are, however, some dual-use manufacturing aspects for lasers. As long as the government and DOD maintain a signal for layered defense using DEWs, industry will improve the SWaP for these systems and generate a price point that will fit within constrained defense budgets.

III. Hypersonic Case Study

A. Stakeholder Interest

In 2015, China successfully tested a hypersonic vehicle.[24] Four years later, China displayed the world's first hypersonic weapon, the DF-17, during a People's Liberation Army parade, claiming the system operational.[25] Following the test, the U.S. quickly resurrected its hypersonic efforts. In 2017, the U.S. conducted its first successful boost-glide hypersonic vehicle test.[26] Seven years later, however, the U.S. still does not have an operational hypersonic weapon. Lack of a strong demand signal and the continued pursuit of industry prototype initiatives have stalled production output. Promptly procuring a limited quantity of hypersonic weapons would signal DOD's intent to begin fielding these systems, allowing stakeholders to repair the broken hypersonic ecosystem.

1. Political

Across the aisle, Congress fully supports hypersonic efforts due to the belief the U.S. trails Russia and China.[27] House members have applauded innovative efforts, such as DOD's Multi-Service Advanced Capability Hypersonics Test Bed and non-traditional defense contractors working on hypersonic technologies.[28] A key question from Congress is the "operational concept" or, put simply, "how will we use" these weapons.[29] Congress also challenges DOD's assertion that hypersonics are strategic weapons given the lack of a strategic warhead, i.e., nuclear.[30] DOD's response is hypersonics are a necessary layer supporting the National Defense Strategy, which supports integrated deterrence with conventional systems as part of a long-range strike option.[31] In turn, DOD plans to focus on air, land, and sea platforms while also developing defensive capabilities, including a resilient sensor layer.[32]

U.S. investment in hypersonics has increased substantially since 2019, from $1.94 billion to $4.7 billion.[33] Additionally, DOD has utilized Congress's middle tier acquisition authority to invest quickly and build prototypes for rapid testing.[34] Congress remains concerned about recent test failures and DOD has responded by highlighting the need for testing capabilities to gain valuable data to inform continued development efforts.[35] Once the first credible U.S. hypersonic weapon is fielded, political stakeholders will likely continue to support the hypersonic weapons needed for the future.

2. Military

At DOD, the pursuit of hypersonics is motivated by several objectives. First, DOD aims to provide decision-makers with effective solutions for evolving security challenges within fiscal constraints, driving a focus on cost efficiency. Second, DOD aims to strengthen the industrial base, enhance production capacity, and bolster supply chain resilience by providing a consistent demand signal. Third, there is an imperative to achieve parity with peer adversaries.[36] Promptly procuring a limited quantity of a credible hypersonic weapons now would accomplish these objectives.

Hypersonics allow DOD to present political leaders with strategic alternatives to conventional means, such as maintaining costly and foreign garrisons, resorting to nuclear options, or embarking on resource-intensive nation-building endeavors. Investment in hypersonics can also efficiently bolster DOD's deterrence posture, augment its operational flexibility, and aid political decision makers to avoid unnecessary escalation.[37]

The U.S. Air Force (USAF) is focused on leveraging hypersonics to achieve effective A2AD penetration. In a Taiwan scenario, hypersonics could swiftly penetrate hostile airspace and establish a strategic foothold, enabling follow-on operations by relatively slower systems.[38] The ability to rapidly gain access with hypersonics enhances the USAF's ability to shape the battlefield and project power in a contested environment.[39]

For the U.S. Army (USA), hypersonics advance long-range precision strike capabilities and strengthen alliances. Hypersonic systems offer a viable alternative to deployed nuclear weapons, allowing the USA to extend its global reach and bolster regional security architectures without the heightened scrutiny and backlash associated with leveraging nuclear weapons.[40] By deploying hypersonics in select nations, the U.S. can reaffirm regional defense postures, foster closer cooperation, and enhance deterrence against potential adversaries.[41]

The U.S. Navy (USN) has two imperatives that drive its pursuit of hypersonics: safeguarding the utility of carrier strike groups (CSG) and enhancing overall operational capabilities. Hypersonic strike will extend the operational reach of CSG air wings, reducing the need for CSGs to enter high-threat engagement areas. By integrating hypersonic systems into their arsenals, the USN bolsters the survivability and effectiveness of its naval assets, fortifying its deterrence posture. The USN also strategically advantages the Joint Force by deploying hypersonics from submarines. Sub-launched hypersonics generate additional uncertainty by threatening critical adversary targets, such as command and control nodes, otherwise protected by A2AD systems.[42]

Pursuing hypersonics across the military services allows them to individually increase their own strategic advantages while collectively expanding adversarial uncertainty, increasing dilemmas for adversaries to solve, and providing political leaders with flexible options to cope with evolving situations. Furthermore, establishing hypersonic programs of record for each service will ensure a constant demand signal to industry, bolstering production capacity, enhancing supply chain resilience, and guiding future development efforts.[43]

3. Industry

The U.S. industrial base is currently focused on producing small quantities of hypersonic and directed energy systems with extended lead times. This situation arises because industry primarily manufactures a product to meet a specific DOD demand.[44] Compounding the problem, DOD remains focused on RDT&E; therefore, deliveries typically consists of small quantity, one-off designs. This approach highlights the need for a shift towards scaling production and enhancing the speed of system deliveries.

Promptly procuring a limited quantity of hypersonics offers significant benefits to industry. It would validate the technology and signal DOD's intent to transition from RDT&E to production. This shift to programs of record will also enable industry to profit and see a return on their investment.[45] Typically, RDT&E funding yields slimmer profit margins, given the government's preference for cost-plus pricing models.[46] Due to limited profit margins, this arrangement discourages industry from substantial internal investment. Moving towards procurement, however, changes this dynamic, providing an incentive to invest in innovation, enhance technology, and maintain competitiveness.

As DOD shifts to procurement, additional benefits emerge. The transition will expand the U.S. market through sales, while allies looking to keep pace will also seek U.S. technologies, further broadening the market. This move would also demonstrate profitability, encouraging more firms to enter the market. The reduced risk associated with return on investment would then make these areas more attractive for competition and innovation. Additionally, the operational deployment of these systems will offer critical benefits to industry developers.

Fielded systems provide an opportunity to gather real-world operational data and user feedback, which is invaluable for refinement and enhancement.

Lastly, fielding hypersonics will generate significant profits from sustainment, which often represents the largest share of the life cycle cost of a weapon.[47] Sustainment includes ongoing maintenance and upgrades and ensures a steady revenue stream for industry over the lifespan of the systems. This revenue is crucial as it supports continued investment in innovation and maintains the health of the industrial base.

4. Allies and Partners

In response to escalating global tensions, the U.S. and its allies and partners have prioritized the development of hypersonic and counter-hypersonic capabilities. The focus to rapidly field a hypersonic weapon has generated increased cooperation between the U.S. and its allies and partners, advancing individual national defense objectives, stimulating economic growth in defense industries, and expediting regulatory reforms for streamlined technology sharing. This collaborative effort has also bolstered a robust global deterrence posture against adversaries. U.S. allies, including Australia, the U.K., Norway, and Japan, have demonstrated commitment to collaboratively develop next-generation capabilities through bilateral partnerships and multilateral agreements, such as AUKUS.[48]

AUKUS members are committed to hypersonic technologies as part of their defense strategies and have demonstrated substantial investment in domestic industries and in U.S.-based commercial efforts. As of May 2024, an enduring impediment to technology collaboration with Australia and the U.K. came closer to resolution as the U.S. Department of State published a proposed rule to amend the International Traffic in Arms Regulations (ITAR) and establish an exemption to the licensing requirement for exports, reexports, transfers, or temporary import of defense articles to or within Australia and the U.K., empowering defense trading, information exchanges, and technology sharing.[49]

Multinational cooperation pursuing hypersonic innovation produces significant U.S. economic and technologic dividends by reducing RDT&E costs, sharing unique technology, and creating increased demand signals. U.S. allies and partners have demonstrated a commitment towards critical emerging technologies associated with hypersonic development and have allocated national resources towards innovation, revitalizing their domestic industrial bases, and investing in partnerships between their governments, industries, and academia.

For example, Australia's 2020 Force Structure Plan earmarked A$30 billion for hypersonic development, testing, and evaluation.[50] In 2022, Australia invested another A$14 million in the Australian Hypersonic Research Precinct, fostering defense, industry, academic, and international collaboration on hypersonic technology.[51] In Europe, the U.K. launched a "Team Hypersonics" to lead developmental hypersonic efforts, which are encapsulated in the £1 billion Hypersonic Technologies and Capability Development Framework Agreement, aimed to bolster U.K. defense capabilities and stimulate domestic technological advancements by supporting the local high-tech industries and job creation.[52]

B. Challenges

The U.S. has not fielded an operational hypersonic weapon because of demand, funding, testing, and supply-chain challenges. These challenges, however, provide opportunity. Promptly procuring a limited quantity of hypersonics will inject new resources into these areas and begin to repair a broken hypersonic ecosystem.

1. Operational Use

The military services have, thus far, provided an unclear demand signal for hypersonics. In 2015, when China tested its first hypersonic glide-body, the U.S. did not have a clear need for hypersonics. This lack of an immediate need created an unclear demand signal to industry. More recently, the reasons for U.S. hypersonics are clear. First, a hypersonic capability is needed to establish deterrence against Russia and China. Second, a low-cost hypersonic is needed as a next-generation missile that will replace existing subsonic weapons. This next-generation hypersonic missile will enhance current U.S. operations and strengthen the force against enemy A2AD systems. These two needs should now translate into requirements for existing DOD hypersonic weapon programs. Promptly procuring a limited quantity of hypersonic weapons to establish deterrence—the first need— would benefit U.S. stakeholders while also stimulating industry to develop the second hypersonic need—a low-cost next-generation missile.

China is developing hypersonics at a rate five to six times faster than the U.S.[53] The reason is because China has a clear demand signal and command economy. China developed hypersonics because they produce new challenges for U.S. short- and long-range missile defense systems, which ultimately challenge the status of U.S. strategic missile superiority. Chinese hypersonics also significantly increased the range of Chinese A2AD systems. The U.S., in comparison, did not develop hypersonics because its military did not require these weapons to defeat Chinese or Russian defense systems. Since China unveiled the DF-17 in 2019, however, the reasons for U.S. hypersonics is now clear in both the near and far term.

First, hypersonics are required to expand U.S. deterrence. The critical capability hypersonics add to deterrence is survivability; U.S. adversaries would be unable to shoot the missile down. In February 2024, the DOD released a report outlining the survivability of Lockheed Martin's Air-Launched Rapid Response Weapon (ARRW). Multiple simulations were conducted to assess ARRW's survivability in a contested environment, which concluded that a single ARRW will complete its mission, despite A2AD missile defenses to detect and engage ARRW in one-on-one scenarios.[54] The DOD noted, "[s]imulations to date indicate that ARRW will meet its survivability requirements."[55] This capability enhances deterrence because it produces a weapon adversaries cannot defeat.

Second, while hypersonics will enhance current operational success, the critical need for operational hypersonics is in future battles. The enhanced capabilities of speed, range, and survivability are all needed in a next-generation missile. Additionally, the U.S. will likely need to produce a large quantity of these weapons, which require the missile to be low-cost, a cost on par with current tactical cruise and ballistic missiles. The U.S. should therefore expeditiously procure a limited quantity of hypersonics to fulfill the deterrence need with a current, proven system such as ARRW. It should then continue to develop low-cost hypersonics to build next-generation missiles.

2. Funding

As cited, the funding required for hypersonics is significant. The USN Conventional Prompt Strike (CPS) and the USA Long-Range Hypersonic Weapon (LRHW) have each received over $1 billion in RDT&E and procurement funding. The USAF Hypersonic Attack Cruise Missile (HACM) has received more than $300 million, while the USN Hypersonic Air Launched Offensive Anti-Surface (HALO) program received $100 million. The DOD requested $150 million in ARRW RDT&E, arguably the only proven hypersonic weapon, but Congress cut this funding with no fight from the USAF.[56]

Although robust, hypersonic funding is sporadic and spread around different services and programs. This allocation has produced duplicity and resulted in the cancellation of proven systems. Like demand, the services and DOD should align funding to programs to produce a limited quantity of the weapons needed today while continuing to pursue the technology needed for the future.

3. Supply Chains

Reliance on exquisite materials for thermal protection could threaten the fielding of hypersonics, but this limitation can be overcome by minimizing the use of systems heavily reliant on these materials.[57] Carbon-carbon and ceramics, the preferred thermal protection materials for use in hypersonic systems, boasts superior durability, oxidation resistance, strength at elevated temperatures, and thermal shock resilience, but each have long lead times, face manufacturing complications, and are threatened by supply chain bottlenecks. Less exquisite materials, such as Inconel or refractory metals, are more available but offer limited resistance to hypersonic speeds above Mach 6.[58]

There are vulnerabilities in the supply chains of these exquisite materials.[59] To mitigate risks, DOD should prioritize materials with accessible compositions. For example, the Hypersonic Air-breathing Weapon Concept and ARRW do not rely on large amounts of exotic materials, instead they utilize materials such as Inconel and stainless steel derivatives, materials more attainable and less vulnerable to supply chain disruptions. Where more exotic materials are required, they are minimized in design, further reducing risks.[60]

Weapon systems relying on more-attainable materials present more-viable options. By focusing on hypersonics in the sub-Mach 6 range, the need for exquisite and high-risk materials is reduced, while the need for high-speed penetration and capability parity is retained. In this lower-end range, high-stress metals can meet requirements and are available in quantity to meet demand. By prioritizing low-end hypersonic options, DOD can expedite deployment while reducing dependence on materials with limited availability. Sparingly fielding higher-end hypersonic glide vehicles (HGV) options that travel in the double-digit Mach range, like LRHW for land-based ally support and CPS for submarines, can ease supply chain pressures by reducing the demand for specialized materials while still bolstering credible political and military deterrence.[61]

4. Testing

Testing infrastructure is rarely a budget priority. In 2022, DOD reported a $5 billion testing and lab deficit and created a steering group to rectify the problem, results from which are to be determined.[62] Developing hypersonic weapons requires specific, high-end testing capabilities and the lack of hypersonic testing infrastructure is a recurring topic mentioned by DOD officials, academics, and industry leaders.[63]

A 1994 National Academies of Sciences, Engineering, and Medicine report outlined that most hypersonic test facilities were built between 1950-1960 and created to support intercontinental ballistic missiles, the space program, and research into first-generation hypersonic vehicles.[64] It concluded that "significant deficiencies must be addressed if the United States is going to maintain a vigorous hypersonic program into the next century."[65] However, it was not until the late-2010s that the U.S. regained its interest in hypersonics. In comparison, China has robust testing infrastructure and has, reportedly, conducted 20 times more hypersonic tests than the U.S.[66]

Consequently, the government, academics, and the industrial sectors face three main constraints regarding testing. The first constraint is availability. Nearly every facility suitable for testing is booked one year or more in advance.[67] Hypersonic programs also compete amongst each other and with other high-priority DOD programs, such as missile defense and nuclear deterrence, generating cascading delays with rescheduling.[68] A second constraint is age. Older facilities are prone to malfunctions, decreasing availability while also lacking efficient data acquisition capabilities. The third constraint is that the characteristics that make hypersonic desirable also make hypersonics difficult to test. At present, flight tests can only be conducted over the ocean, requiring sensors on boats that take weeks to emplace. This means DOD can only conduct four to six tests per year.

Multiple initiatives are in progress to mitigate the lack of test facilities. The Principal Director for Hypersonics within the Office of the Secretary of Defense wants "to open the aperture to allow the national team to learn at the pace of discovery and not at a pace limited by the availability of flight-test range windows."[69] His goal is to reach one flight test per week. Industry and academic institutions are also developing new facilities[70] and Congress appears poised to support. In a report accompanying the FY23 National Defense Authorization Act, the Senate Armed Services Committee noted, "one of the greatest concerns of the committee is the ability to test hypersonic systems, which requires extensive range space and sophisticated testing capabilities."[71] Finally, the U.S. is looking at expanding its flight-testing capabilities through ally and partner facilities.

Seven years after first testing a hypersonic glide body, DOD has yet to field an operational system. Demand, funding, supply chain, and testing challenges all contribute to this result. The services have delivered a weak demand signal, attempting to balance a weapon needed for deterrence today against a weapon needed in the future. Funding has followed demand by sporadically resourcing various programs. Exotic materials have also created bottlenecks, hindering development. Lastly, limited and antiquated testing infrastructure has neutered research. Addressing these challenges would expedite the fielding of a U.S. hypersonic weapon.

IV. Directed Energy Case Study

A. Stakeholder Interest

The new era of drone warfare, complemented by traditional missile attacks, as witnessed in Israel, Ukraine, and the Red Sea, generate the need for more-efficient defenses. While U.S. defensive missiles can neutralize these threats, the cost of doing so is expensive and non-sustainable. Using a million-dollar missile to target a thousand-dollar drone is a strategically unwise, regardless of the value of the protected asset because the offense will maintain the economic advantage to simply procure more. This balance is offset even more as limited missile stockpiles dwindle. Despite this, the U.S. has been slow to field cost-efficient DEWs. Part of the problem lies in the slow, political-military-industry relationship of moving from prototype to operational system. The end user also lacks confidence in DEWs and is reluctant to employ them over proven, kinetic options. Finally, the U.S. has been slow to leverage its allies and partners for their exponential advancements in DEWs. Fielding available and viable DEW systems now will stimulate industry and provide battlefield results that will bolster user confidence. Leaning on partner capabilities in operational and testing environments will then consolidate allied gains.

1. Political

In 2020, the House Armed Services Committee published a report focused on the future of national defense, which identified directed energy as a cost-effective solution to an array of threats.[72] Congress has provided robust funding for DEWs since, including nearly $1 billion in FY24.[73] Congress, however, remains concerned about the maturity of the technology and its utility across military missions.[74]

DEWs were recently highlighted by General Michael Kurilla, Commander of U.S. Central Command (CENTCOM), during testimony before the Senate Armed Services

Committee, when he discussed the constant threat of Houthi missiles and drones in the Red Sea.[75] General Kurilla indicated the USN has fielded some DEW platforms in CENTCOM, but he "wished the Navy would send more."[76] Congress is acutely aware of the cost advantages DEWs offer against missile and drone threats versus conventional systems,[77] but DOD must still weigh the maturity of this technology against the end user's confidence in employing these systems.

2. Military

DEWs represent a significant advancement in military technology.[78] Beneficiaries include the services, industry, government, and even civilian populations. Procuring DEWs will provide military forces with a strategic advantage over potential adversaries because they have the potential to disrupt enemy operations, degrade capabilities, and undermine confidence, all at low cost.[79]

The USA and U.S. Marine Corps see benefits from DEWs for enhanced ground-based capabilities and the ability to engage and neutralize threats with minimal collateral damage. DEWs could also be used for precision strikes against enemy targets, including vehicles, drones, and even personnel. For example, The USA's HEL Mobile Demonstrator is a directed energy system designed to provide a mobile, ground-based defense against aerial threats, particularly small drones and incoming mortar rounds.[80]

The USN already utilizes DEWs for ship-based defense. DEWs offer rapid response and precise targeting, effective against missiles, small boats, and unmanned aerial vehicles (UAV). Another notable directed energy system in progress is the USN's Laser Weapon System, which is currently deployed on a limited number of naval vessels and is designed to operate using a HEL to disable or destroy targets through precision engagement.[81]

DEWs also provide the USAF with options for aerial combat and missile defense. They can be integrated into aircraft for air-to-air engagements or deployed as ground-based systems to intercept incoming missiles. The USAF has been exploring DEWs for various applications, including the Airborne Laser (ABL) program, which aimed to mount a chemical oxygen iodine laser on a modified Boeing 747 aircraft for missile defense purposes.[82] While the ABL program was discontinued, it demonstrated the potential for intercepting and destroying ballistic missiles during their boost phase.

Overall, DEWs offer scalability and adaptability and allow for flexible deployment in various operational environments. They can be integrated into platforms or deploy as standalone systems. This versatility enables military forces to respond effectively to evolving threats and changing tactical situations. The procurement of DEWs offers numerous benefits to military stakeholders, including enhanced combat capabilities, cost savings, improved force protection, and strategic advantage.

3. Industry

Similar to hypersonics, the directed energy market likewise suffers from a lack of consistent demand signal.[83] DOD allocates $1 billion annually towards developing DEWs, encompassing HELs and HPMs.[84] Despite this, and also similar to hypersonics, DOD has yet to procure and field any significant DEW capability.

The ongoing conflicts in Ukraine and Israel highlight the need for affordable weapons with the capacity to counter kinetic threats such as UAVs.[85] DEWs, known for their low cost per engagement, address this crucial requirement. The industrial base for DEWs is currently limited to producing small quantities of systems with extended lead times.[86] Like hypersonics, defense companies primarily manufacture to meet DOD demand, seldom producing beyond these specifications or innovating independently.[87] Hence, current deliveries are one-off systems. The time is ripe for DOD to shift toward production.

Procuring limited quantities of fielded DEWs will validate RDT&E and signal industry is capable of transitioning to full deployment. This shift will enable industry to reap profits, which can be turned towards further advancements in DEWs.[88] Because current profit margins are limited in RDT&E, companies are discouraged from making substantial internal investments without a signal to scale for deployment. Moving to procurement will provide an incentive for industry to re-invest in its own systems to advance technologies and remain competitive. A limited procurement will further stimulate development and ensure future procurement. Additionally, fielding a limited amount of DEWs will expand the market. Finally, when the U.S. fields DEWs, this will likely set the international standard, and other nations will seek to acquire similar technologies, further expanding the U.S. market.

Transitioning to procurement will also encourage more companies to enter advanced technical domains. Increased return on investment and reduced risk will increase the attractiveness to compete and innovate in HEL and HPM technology. Moreover, deployed DEW systems offer the opportunity to gather operational data and feedback, which help to refine systems for future demands. Finally, fielding DEWs now creates sustainment profit, usually a large share of the life cycle cost of a weapon system, by guaranteeing consistent revenue for industry over time.[89] Consistent long-term revenue is an industry requirement because it benefits the innovation and health of the industrial base.

4. Allies and Partners

DOD's investment in directed energy benefits the U.S. and its allies and partners by bolstering regional stability and enabling superior integrated defense systems.[90] AUKUS members, and U.S. partners like Israel and Japan,[91] are driving DEW development in complementary technology areas. Moreover, these allies and partners benefit from direct U.S. investment in domestic DEW programs and capabilities as DOD actively funds international HEL and HPM technology.[92] DEWs significantly improve operational flexibility and integrated defense against global threats while enhancing the effectiveness of existing missile defense systems and increasing interoperability in a robust collective security architecture.[93]

For example, Australia's strategic investment in DEWs is evident in its 2020 Force Structure Plan, as the Australian Defense Force has actively incorporated DEW systems into its military strategy, focusing on regional stability and deterrence capabilities, while conducting joint exercises with U.S. forces to increase interoperability.[94] To develop emerging technologies like DEWs, the Australian government pledged A$3.4 billion over the next decade to establish the Advanced Strategic Capabilities Accelerator. These funds provide an additional A$591 million above planned defense innovation spending.[95]

In Europe, the U.K. Ministry of Defence (MOD) is following a three-year "Transition Phase" program in anticipation of a pivot to operationalize DEWs within the next decade for air defense and counter-UAV applications. User experiments are planned for 2024, supported by collaboration with DOD. During a trial at the MOD Hebrides Range, the Defence Science and Technology Laboratory test fired DragonFire, which became the first U.K. high-powered laser to successfully strike an aerial target.[96] Its reported accuracy is described as striking a £1 coin one kilometer away. Enhancing bilateral collaboration on DEW technologies, such as radio frequency systems for air defense and counter-unmanned aerial system applications, signals U.K.'s commitment to advanced defense capabilities.[97]

DEW development and deployment also present significant economic advantages for the U.S. and its allies and partners.[98] Collaboration stimulates domestic industries' innovation, creating jobs and economic growth. DEWs' cost-effectiveness, compared to traditional munitions, also offers the potential for long-term defense budget savings. Partnerships like AUKUS promote technological sovereignty, bolster local industrial capabilities, and reduce reliance on imported systems.[99] With the 2024 amendments to ITAR, the prospect of an added ease of trading, technology sharing, and export options should bolster the economic activity between the U.S. and AUKUS members.[100]

B. Challenges

DEWs are an emerging technology that creates unique challenges. New supply chains and production capabilities must be created. To field them, funding and contracts must address RDT&E, procurement, and sustainment.

1. Operational Use

Without operational experience, DOD cannot determine how DEWs will be integrated into layered defense. DOD needs clearly articulated strategic goals for DEWs to ensure these systems can be produced and integrated into its strategic framework.[101] Failing to field available systems that demonstrate a minimally viable capability, however, is a missed opportunity to determine strategy. Industry is interested in the operational use of their systems to verify their effectiveness, help determine how they should be integrated, and identify the required volume of systems.[102] To reduce costs, DEWs should be deployed and the systems must be reliable. If not, DOD will face continued challenges with testing restrictions and without operational feedback.

DEWs will reduce the cost per engagement, and once the initial investment in DEW infrastructure is made, the operational cost per shot is relatively low.[103] Also, DEWs' ability to intercept and neutralize incoming projectiles reduces the risk of casualties and damage to military assets, thereby increasing survivability on the battlefield. DEWs offer unparalleled precision in targeting enemy assets as well. Unlike conventional weapons, which rely on physical projectiles or explosives, DEWs deliver energy at the speed of light with pinpoint accuracy.[104]

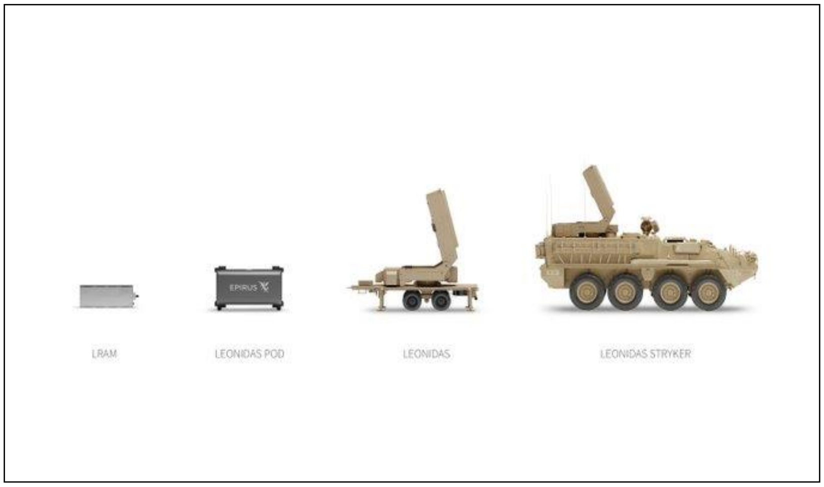
While the initial investment in DEWs may be significant, the operational costs are relatively low compared to the ongoing expenses associated with purchasing, transporting, and maintaining conventional ammunition.[105] DEWs, however, require significant power generation and cooling systems to operate effectively. Generating and sustaining high energy levels can strain existing power infrastructure and necessitate the development of specialized power sources. Additionally, managing thermal loads and dissipating excess heat generated by DEWs is essential to prevent overheating and ensure continuous operation.[106]

Overall, even as the operational use of DEWs offers numerous benefits, DEW technology is still in the early stages of development and may not be mature or reliable enough for widespread deployment. Achieving technological maturity requires continued investment in RDT&E to address performance limitations and ensure operational readiness.[107] Additionally, integrating DEWs into existing military platforms and command and control systems poses technical challenges that must be overcome to maximize their effectiveness in combat. Addressing these challenges requires a coordinated effort involving RDT&E and strategic planning to leverage the full potential of DEWs in modern warfare.

2. Funding

Contracting practices do not support the rapid development and fielding of DEWs. For HELs, the company nLight emphasizes its modular and scalable Coherent Beam Combined architecture.[108] For HPMs, the company Epirus demonstrates scalability through its Line Replaceable Amplifier Modules (LRAM) and open Application Program Interface for easy integration with other systems.[109] According to multiple field study respondents, the challenge is that government contracting and development protocols do not emphasize production, opting towards single-unit prototype milestones that may or may not be scalable.[110]

If DEWs are developed with an open architecture, allies' interest in U.S. manufactured systems is likely to increase. They could be upgraded or maintained based on open architecture standards for standard components like LRAMs, easily integrated, replaced, or upgraded in a variety of configurations, where additional LRAMs allow for higher-power systems. Figure 4[111] shows the flexibility allowed through the Epirus scalable architecture. Without a common architecture, allies and partners may pursue independent development, compete for resources, and face increasing integration and support challenges.



[Figure 4: Epirus Scalable Architecture Based on Common LRAM]

Inconsistent funding and direction for DEWs also prevent industry from building a production base. In light of global events, DOD officials desire to deploy DEWs rapidly.[112] Despite this urgency, DOD's focus is to continue pursuing larger, more powerful systems over deploying existing capabilities.[113] Industry believes production ready systems exist now that could be deployed to active theaters like Ukraine and Israel. Operational use on a current battlefield would inform future upgrades, establish a true demand signal, and increase user confidence.[114]

3. Supply Chains

HELs and HPMs are complex systems with several key components and Chinese-linked supply chain risks.[115] HELs rely on germanium, gallium, erbium, and other elements from markets primarily controlled by China.[116] Other components, like high-purity silica used in optical fibers for fiber lasers, face single-source supplier challenges.[117] Batteries used in DEWs are also primarily sourced from different nations and are in demand globally. Figure 5 provides an overview of the global distribution of critical materials used in DEWs, including their source country and a heat map of the supply's relative vulnerability.[118] Nearly all are vulnerable. DEWs face additional supply chain threats for key components like advanced optics. The overall supplier market for advanced optics is broader due to non-military uses. However, based on industry study site visits, optical suppliers for large beam directors for high-energy systems are limited.

In field study meetings with DEW producers, both for HEL and HPM systems, producers expressed frustration at maintaining production lines without a consistent demand signal from the government. In cases where supplier options exist to service commercial products, they stated that the market capability remains, but suppliers are likely to pursue more consistent commercial demand. In cases where the market is limited to the military, like with very large beam directors for high-power systems, suppliers may divest from the market.

Materials	Top Producers	Vulnerability	Explanation
Rare Earth Elements	China, U.S., Australia		China dominates mining and processing.
Silicon	U.S., Norway, Brazil, Russia, China		This is a highly diverse supply chain with Canada and other friendly countries contributing to most U.S. imports.
Gallium	China, Canada,, Japan, Russia, South Korea, United States		The U.S. depends on China for a majority of imports, and China has added new export controls.
Germanium	China, Canada, Russia, Finland, United States		A large reliance on China for imports which may be affected by new export controls.
Barium Titanate	China, India, Morocco, United States		Reliance on Chinese imports and hydrocarbon industry demands increase vulnerability.
Aluminum	China, India, Russia, Canada		Half of U.S. imports are from an ally.
Ammonia	China, Russia, United States, India		U.S. industry is growing and decreasing import needs.
Copper	Chile, Peru, Democratic Republic of the Congo, China, United States		Domestic ore refining and processing difficulties and U.S. domestic permitting challenges may allow China to dominate the market.
Lithium	Australia, Chile, China, Argentina		Raw lithium is sourced from Argentina and Chile, but the majority of lithium-ion batteries are imported from China.
Graphite	China, Madagascar, Mozambique, Brazil		China dominates the industry with increasing growth in U.S. capabilities.
Nickel	Indonesia, Philippines, Russia, New Caledonia		U.S. imports from friendly nations, but China has the most processing capabilities.
Manganese	South Africa, Gabon, Australia, China		Current supply is stable due to strong demand in the steel industry.

[Figure 5: Critical Materials in DEWs]

4. Testing

Test-driven development drives the ability to quickly develop, produce, and deploy new technology like emerging hardware systems.[119] DEW manufacturers like Epirus and others use agile techniques to design and upgrade systems rapidly.[120] However, multiple manufacturers remarked that government practices should focus more on testing. They felt the government displays very low test-risk tolerance, preventing rapid product improvements.

While not engaged in DEW development, the Space X philosophy of "test, fail, fix, repeat" displays what agile hardware development companies strive for to quickly develop and deliver new capabilities.[121] The Space X approach is not possible with low-risk tolerance and a focus on infrequent, significant pass-fail testing. Producers face further challenges for directed energy systems with limited range availability and Federal Aviation Administration approval restrictions on atmospheric system tests.[122]

V. Adapting to New Realities

Over the span of six months, the Weapons Industry Seminar conducted comprehensive engagements with key leaders and stakeholders across the hypersonic and DEW enterprises. In parallel, the Seminar undertook extensive open-source research to enhance their collective understanding and knowledge of the environments surrounding these emerging technologies. Although limited to an unclassified setting, key findings and trends surfaced from nearly all stakeholders.

Emerging technologies continuously transform the character of war, with hypersonics and DEWs at the forefront of this current evolution. Peer adversaries have developed and fielded hypersonic capabilities, posing significant challenges to the U.S.'s technological supremacy in current and future conflicts. Furthermore, the ongoing conflicts in Ukraine and Israel highlight the economic strains involved when low-cost, weaponized UAVs are countered using expensive kinetic interceptors.

The U.S. is adapting to these changes within the hypersonic and DEW domains. As it aggressively pursues advancements in these high-cost technologies, several challenges continue to hinder serious progress. Concerns regarding affordability and the operational necessity of these technologies often arise as counterarguments. Additionally, the U.S. is extensively engaged in RDT&E activities, yet faces hurdles in moving to large-scale production. These obstacles—including an unclear demand signal, inadequate testing infrastructure, underdeveloped supply chains, inconsistent funding, and underutilized allies and partners—hinders the transition from experiment to production. To overcome these challenges, DOD should implement the following recommendations.

A. Create Central Authorities for Hypersonic Development

To effectively determine the operational needs for hypersonics, DOD should establish a formal Joint Hypersonics Office (JHO). This office would serve as the central authority overseeing all hypersonic performance requirements, ensuring strategic alignment across the services and with Congress, and establish joint doctrine and training. Our research and interaction with the hypersonic community indicates an ad hoc pursuit across the services and within DOD. In comparison, a centralized approach to hypersonic technology will synchronize and integrate capabilities and objectives while avoiding redundancy and duplicity.

Once established, the JHO should first conduct an operational analysis to assess the necessity of hypersonics in current and future threat scenarios. As part of this analysis, it should evaluate the performance requirements and quantities necessary to deter, and if needed defeat, current and future threats. A cost-efficiency analysis should also establish the optimal balance between hypersonic munitions and existing stockpiles. This analysis will maximize the “cost to defeat” value, ensuring the most economically and strategically effective deployment of resources.

Upon completion of the operational assessment, the JHO should then establish performance requirements and quantities for a near-term capability to be fielded to address the current threat scenario. It must then develop a long-term capability strategy focused on future advancements in the hypersonic domain based on future threat scenarios. Organizing hypersonic efforts into a central, joint office with responsibilities over the entire hypersonic program will ensure efficiencies and align efforts to generate and promptly field an operational hypersonic weapon.

Next, and to optimize the development of hypersonic technologies, the DOD should establish a formal Joint Hypersonic Acquisition Authority (JHAA). This office would serve as the central authority overseeing all hypersonic development and production efforts, actively managing resources to maximize value while synchronizing and deconflicting ongoing efforts. Based on the JHO’s defined near-term capability, the JHAA should first thoroughly review ongoing development programs in both the U.S. and its allies and partners. This evaluation will determine whether these efforts align with and fulfill the current operational requirements. The findings from this assessment will inform strategic decisions later, either advancing programs towards production or adjusting development strategies to better meet near-term needs.

The DOD should also task the JHAA with formulating a comprehensive research and development plan. This plan will support and advance the strategic objectives laid out by the JHO, ensuring that development efforts are systematically aligned with the overarching goals for hypersonic technology advancement. The JHAA should then perform a comprehensive supply chain assessment. This evaluation will determine the current status of the supply chain and identify areas where investments are necessary to support both immediate and future objectives. This assessment will ensure supply chain developments are effectively aligned with the overarching goals of the hypersonic programs. Finally, DOD should task the JHAA to comprehensively evaluate the existing testing infrastructure. This assessment will determine the adequacy of current facilities and serve as the foundational step in developing a targeted investment strategy to enhance and expand testing. This strategy will ensure that the infrastructure fully supports the evolving needs of hypersonic development and deployment.

Creating central authorities for hypersonic development will solve multiple challenges identified by stakeholders and from independent research and evaluation. First, joint efforts can synchronize messaging to industry, the most-common challenge recorded from industry partners. This will ensure consistent and clear communication with industry partners to align their investment and production efforts with DOD's strategic needs and timelines.

It would also enhance information sharing and facilitate information exchange to prevent information silos, while ensuring all program offices and research facilities are aware of ongoing efforts, technological advancements, and strategic insights. Central authorities will also eliminate redundancies. Joint offices can actively identify and eliminate overlapping efforts across different projects, streamlining resources and focusing on unique, value-adding activities. These recommendations will optimize cost efficiency and integrate cost saving measures in the design and development phases, focusing on long-term sustainment and affordability to reduce the total lifecycle costs of hypersonic technologies.

Finally, central authorities can coordinate test resource utilization and coordinate across allies and partners for interoperability. Testing availability was an often-cited concern from developers. A central office could develop a comprehensive scheduling and resource allocation system to deconflict the use of critical test facilities and resources, enhancing the efficiency of development timelines and reducing bottlenecks. This centralized approach will also talk with allies and partners in one voice. During the development phase, a centralized approach will prioritize design elements that enhance exportability and leverage allies' and partners' research and production capabilities. This approach will also facilitate smoother integration and broader use of the developed technologies across international lines, ensuring that our systems are adaptable and compatible with those of our allies and partners

B. Prioritize Directed Energy Partners

Within directed energy, DOD should prioritize collaboration with allies and partners to optimize the development, testing, and coalition fielding of DEWs. This approach will leverage mature DEW technologies available from allies and partners, streamlining the DOD's $1 billion annual DEW spending and accelerate the transition from prototyping to operational systems. [123] Additionally, collaborating expands testing opportunities, aiding U.S. industries in refining DEW systems for deployment. Ultimately, acquiring or co-developing DEW technologies bolsters U.S. capabilities, ensures technological interoperability, and resulting in a more cohesive, robust multinational defense posture.

There are multiple steps DOD can make with its allies and partners to operationally field DEWs. First, to ensure the long-term interoperability, compatibility, and sustainment of DEWs, DOD should spearhead the development of a comprehensive modular open system approach (MOSA) framework in close collaboration with multinational stakeholders. Strategic alliances with multinational security entities such as AUKUS or the North Atlantic Treaty Organization (NATO), and trusted allies like Israel and Japan, are essential for advancing MOSA principles.

By establishing universally-accepted software standards and stringent cybersecurity protocols for component development, DOD will gain the flexibility to integrate both mature and emerging technologies. This approach fosters a scalable and adaptable DEW architecture that can evolve alongside the operational needs of the U.S. military and allied forces.[124]

The ability to develop DEWs through a MOSA framework is the technological backbone, ensuring these diverse systems work seamlessly together for maximum effectiveness.[125] A comprehensive security approach is likewise crucial. For consideration, the U.K.'s 2023 "Five-Pillar Model" called for deterrence, active defense, and passive measures through jointly identifying key vulnerabilities, uniting the sector to benefit from shared national resources and expertise, and integrating security measures into the framework of emerging technologies to prevent cyber-attacks.[126] A MOSA framework would ensure DEW systems avoid being locked into obsolete technologies or proprietary interfaces. This flexibility allows for seamless updates and upgrades, ensuring long-term system viability and adaptability to evolving threats.

Second, and to bolster near-term defense capabilities and enhance vital defense partnerships, DOD should strategically assess the acquisition of mature foreign DEW technologies like Israel's Iron Beam or U.K.'s DragonFire. Developed in partnership between the Israeli defense firm Rafael and Lockheed Martin, with a $1.2 billion U.S. investment and an expected 2025 initial operating capability (IOC), the Iron Beam 100-kilowatt system presents an opportunity to pursue an accelerated technology transfer, collaborating to create interoperability and supplement ongoing U.S. DEW development programs such as the Indirect Fire Protection Capability-High Energy Laser.[127]

Third, to streamline DEW development, the DOD should establish a formal testing partnership with Australia, utilizing the less restrictive environment of the Klondyke Range

Complex. This partnership would address the limitation of domestic testing regulations and offer dedicated facilities for high-power laser systems. The Klondyke Range Complex houses high-power laser research and development labs, sensors capable of operating and analyzing high-power lasers, advanced fabrication equipment, and additive and subtractive manufacturing capabilities.[128] While the cost of moving DEW systems to Australia for testing is high, an Emerging Technology Institute report determined the benefits of less restrictive testing windows outweigh these expenses.[129] At least 31 directed-energy initiatives are underway across the U.S. military. The Klondyke Range Complex would provide the infrastructure and expertise necessary for expanded and rapid DEW testing, directly benefiting ongoing DOD DEW programs such as High Energy Laser with Integrated Optical-dazzler and Surveillance, Leonidas, High-Energy Laser Weapon System, and other systems.[130]

Finally, the ongoing conflict in Ukraine presents a unique opportunity for the U.S. and its partners to accelerate the development and fielding of next-generation DEW technologies. The U.S. and U.K. should quickly deploy operationally-ready HEL and HPM systems like Directed Energy Maneuver Short-Range Air Defense (DE M-SHORAD) and DragonFire for rigorous testing and validation against real-world threats. This combat-derived data will then inform rapid system refinement, bolster warfighter confidence in DEW capabilities, and generate a robust demand signal.[131] The USA's February 2024 deployment of four M-SHORADs in CENTCOM, and NATO allies imploring the U.K. to deploy its DragonFire system to Ukraine, indicate the time is ready to deploy DEW systems to active combat zones as part of the RDT&E process, underscoring these systems' immediate value and potential.[132]

VI. Conclusion

Hypersonics and directed energy, two critical technologies vital to national defense, are changing the current character of war. Some even argue these emerging capabilities, when coupled with additional technologies such as autonomous systems and artificial intelligence, may change the very nature of war. The confluence of these systems is creating a future battlefield that will be void of humans, where reaction to autonomous systems operating in swarm and at hypersonic speed is only recognized and defeated by operating on a decision cycle faster than human understanding.

Since victory in the Second World War and its rapid rise to global hegemon, the U.S. has faced few peers and led the world in innovating, procuring, and manufacturing advanced weaponry. The strategic environment, however, has changed and the U.S. no longer leads the world in certain technological domains. Peer adversaries with their command economies now challenge U.S. technology and power, but it is not American intellect or ingenuity that lags its rivals; it is American bureaucracy with its ongoing tendencies for risk-aversion and perfection seeking during RDT&E followed by a less-than-informed procurement strategy.

The future, though, is bright. U.S. industry, DOD, and Congress all recognize these current challenges and the changing landscape and have devoted significant efforts and funding to field these systems. But to fully embrace and quickly field these emerging technologies that are crucial for future competition and containment, the U.S. must act differently. It must identify required capabilities for the current and future operating environment and embark on a risk-tolerant development and test strategy. The U.S. should also centralize control over the development and procurement of hypersonics at the DOD-level, streamlining performance requirements and ensuring strategic alignment across the services and with Congress while establishing joint doctrine and training to address current and future operational needs. This centralized office would also manage resources to maximize value while synchronizing and deconflicting ongoing efforts.

Additionally, the U.S. will not fight in the future alone, and any future conflict will be heavily dependent on U.S. allies and partners. Within the DEW market, the U.S. should embrace and rely upon these partnerships, prioritizing collaboration and optimizing the development, testing, and coalition fielding of DEWs. Partner DEW systems exist, are successful, and offer the U.S. a unique opportunity to benefit from partner efforts and investments.

The future battlefield exists today and emerging technologies such as hypersonics and directed energy will provide the U.S. the capabilities needed to respond in competition and containment. Adversaries may lead in some areas now, but U.S. opportunities exist. Streamlining internal actions while intensely coordinating with allies and partners offers the U.S. solutions to maximize these systems and put forth a Joint Force able to guarantee U.S. national security objectives.

APPENDIX A
Norway and Japan Benefit Perspective

While not formally included in AUKUS, Norway and Japan are actively pursuing hypersonic and counter-hypersonic technologies. Norway's 2024 Long-Term Defense Plan will double its defense budget over the next 12 years with a $60 billion investment focusing on short-range ballistic missile defense and allied capability enhancement.[133] By acquiring counter-hypersonic capabilities, Norway could contribute to NATO's deterrence posture, particularly in the North Atlantic and Arctic regions.[134]

Norway's strategic emphasis on integrating hypersonic technologies has enhanced testing and evaluation capabilities, notably by adapting sites like Andøya and Bardufoss. Norway seeks to be an attractive partner for international collaboration to drive growth in its defense and technology industries.[135] Key domestic stakeholders supporting this trajectory include Nammo, a leader in ramjet propulsion development, and Kongsberg, a contributor to advanced missile technologies.

Japan, through its 2023 security documents, formalized its commitment to Indo-Pacific security by developing hypersonics primarily in defense of its sovereignty, often collaborating with the U.S. on relevant projects to counteract regional threats.[136] Japan's investment in these technologies, including the development of HGVs and scramjet-powered missiles, have been featured in DOD-Japan collaborations such as the Glide Phase Interceptor and the advanced interceptor missile project Standard Missile-3 Block IIA. Japan is also partnering with the Missile Defense Agency for the Hypersonic and Ballistic Tracking Space Sensor prototyping program.[137]

Japan strategically invests in hypersonic technologies to bolster its defense against regional threats and drive technological innovation. This investment stimulates growth in advanced materials and aerospace industries, enhancing Japan's industrial base and strengthening its position in the global supply chain for advanced defense technologies. Key players include Mitsubishi Heavy Industries (hypersonic propulsion and missiles), IHI Corporation (aerospace and propulsion expertise), and the Japan Aerospace Exploration Agency (hypersonic flight dynamics and heat resistance research).[138]

APPENDIX B
Japan and Israel Benefit Perspective

1. Bilateral Political and Operational Benefits

In the 2023 Japan Defense Technology Strategy (JDTS), the Japanese Ministry of Defense indicated a desire for HEL capable of instantaneous and persistent engagement against saturation attacks, especially by cruise missiles. The JDTS also called for a system capable of emitting an electromagnetic pulse, to attack enemies at the speed of light and with unlimited ammunition.[139] Japan's collaboration with the U.S. HPM systems, supported by security agreements, advances its counter-drone DEW capabilities.[140] Companies like Mitsubishi (100-kilowatt system) and Kawasaki (10-kilowatt system), drive Japan's DEW progress, with successful drone-countering laser tests.[141] These efforts highlight Japan's response to regional security concerns from North Korea and China and its commitment to enhancing self-defense capabilities. Japan's DEW integration into alliances like AUKUS would boost operational capabilities and interoperability, strengthening collective military preparedness against shared threats.

Israel's integration of DEW systems, such as Iron Beam, demonstrate its strategic emphasis on countering missile and drone threats from an active defense posture. Israel derives many benefits from the U.S., as the U.S.-Israel Directed Energy Cooperation Act (DECA), embedded in the FY21 National Defense Authorization Act (NDAA), solidifies bilateral collaboration, enhancing joint development and deploying DEWs.[142] DECA facilitates joint development, testing, and deployment of DEWs to tackle mutual security threats. The U.S. has pledged $1.2 billion toward the procurement of Israel's Iron Beam, capable of defeating UAVs, mortars, and rockets and engaging multiple targets from several kilometers away. Successfully tested in 2022, the Lockheed Martin and Rafael-designed system is expected to be fielded by the

Israel Defense Forces by 2025. The FY23 NDAA extends U.S.-Israel collaboration on anti-drone DEW technologies, increasing funding and extending the program through 2026, raising the cap on annual U.S. contributions to the program from $25 to $40 million.[143]

2. Japan and Israel Economic Benefits

Japan and the U.S. have established a Memorandum of Understanding for Research, Development, Test, and Evaluation Projects for emerging defense technologies, including HPM systems.[144] Japan's investment in counter-drone DEWs, supported by U.S. collaboration, fuels domestic innovation in electronics and materials science, strengthening its defense industry, creating high-tech jobs, and contributing to overall economic growth. Japan's supply of critical components, such as neodymium, makes it a vital partner in the global DEW supply chain. This mutually beneficial relationship mitigates supply risks while enhancing Japan's position as a technological leader, furthering its defense autonomy. Japanese companies like Mitsubishi and Kawasaki demonstrate the nation's DEW capabilities with adaptable counter-drone laser systems.[145]

Israel's DEW collaboration with the U.S., solidified by the DECA, has catalyzed its defense industry's innovation and growth.[146] The Iron Beam system exemplifies this strategic partnership's operational and economic benefits. Rafael Advanced Defense Systems' development of the Iron Beam underscores Israel's commitment to technologically advanced, cost-effective defense solutions. This system bolsters Israel's multi-layered defense against short-range threats. Increased U.S. investment in Israeli DEWs will drive economic growth, fosters high-tech industries, and secures a robust supply chain critical for both nations' defense strategies.[147]

[1] Joeseph Biden, "National Security Strategy," White House, October 12, 2022, p. 2, https://www.whitehouse.gov/wp-content/uploads/2022/11/8-November-Combined-PDF-for-Upload.pdf.

[2] Stuart Winer, "Report: Gulf States, Including Saudi Arabia, Provided Intelligence on Iran Attack," *The Times of Israel*, April 15, 2024, https://www.timesofisrael.com/report-gulf-states-including-saudi-arabia-provided-intelligence-on-iran-attack/.

[3] Andrew Macaskill, "Israel's Defences Would Trump Iran's in any Air War, but at a High Cost," *Reuters*, April 18, 2024, https://www.reuters.com/world/middle-east/any-air-war-israels-defences-would-trump-irans-high-cost-2024-04-18/.

[4] "Israelis Fired 3 Missiles in Limited Strike," *ABC News*, April 19, 2024, https://abcnews.go.com/International/live-updates/israel-gaza-hamas-war/israelis-fired-3-missiles-in-limited-strike-109428614?id=108860743.

[5] Biden, "National Security Strategy," p. 23.

[6] Kelley M. Sayler, "Hypersonic Weapons: Background and Issues for Congress," Report 45811, Congressional Research Service, February 9 2024, p. 4, https://crsreports.congress.gov/product/pdf/R/R45811/38.

[7] Heidi Shyu, Undersecretary for Defense for Research and Engineering Memo, "Technology Vision for an Era of Competition," February 1, 2022, https://www.cto.mil/wp-content/uploads/2022/02/usdre_strategic_vision_critical_tech_areas.pdf.

[8] "Hypersonic" is an adjective naming an attribute of any vehicle body, that attribute being the capability of travel at or beyond Mach 5. For the purposes of this paper, all reference to "hypersonic weapons" or merely "hypersonics," refers to land, sea, or air launched missiles that travel at speeds beyond Mach 5.

[9] Masao Dahgren, "Getting on Track: Space and Airborne Sensors for Hypersonic Missile Defense," Center for Strategic and International Studies, December 2023, https://csis-website-prod.s3.amazonaws.com/s3fs-public/2023-12/231218_Dahlgren_Getting_Track_0.pdf?VersionId=gyTyKePGJmFvnZmTgQY5._GidZ0jfGh4.

[10] Michael R. Gordon, "China's Hypersonic Missile Test Is Close to 'Sputnik Moment,' U.S. Military Chief Says," *The Wall Street Journal*, October 27, 2021, https://www.wsj.com/articles/u-s-military-chief-says-chinas-hypersonic-missile-test-is-close-to-sputnik-moment-11635344992.

[11] Sayler, "Hypersonic Weapons," p. 1.

[12] Mikayla Easley, "AUKUS Partners Aim to Catch China in Hypersonics Race," *National Defense*, February 17, 2023, https://www.nationaldefensemagazine.org/articles/2023/2/17/aukus-partners-aim-to-catch-china-in-hypersonics-race.

[13] Sayler, "Hypersonic Weapons," p. 2.

[14] R. Jeffrey Smith, "Hypersonic Weapons are Unstoppable. And They're Starting a New Global Arms Race," *New York Times Magazine*, June 19, 2019, https://www.nytimes.com/2019/06/19/magazine/hypersonic-missiles.html.

[15] Jonathan Lehrfeld, Diana Stancy, and Geoff Ziezulewicz, "All the Houthi-U.S. Navy Incidents in the Middle East (That We Know Of)," *Military Times*, May 1, 2024, https://www.militarytimes.com/news/your-military/2024/02/12/all-the-houthi-us-navy-incidents-in-the-middle-east-that-we-know-of/.

[16] Mordor Intelligence, “U.S. Defense Industry Size and Share Analysis - Growth Trends and Forecasts (2024 - 2032),” accessed May 1, 2024, https://www.mordorintelligence.com/industry-reports/united-states-defense-market.
[17] Id.
[18] U.S. Department of Defense, “National Defense Science and Technology Strategy 2023,” May 2023, https://www.cto.mil/wp-content/uploads/2023/05/2023-NDSTS.pdf.
[19] Michael E. Porter, “How Competitive Forces Shape Strategy,” *Harvard Business Review*, May 1979 (Vol. 57, No. 2), pp. 137-145, https://hbr.org/1979/03/how-competitive-forces-shape-strategy.
[20] Sayler, “Hypersonic Weapons,” p. 2.
[21] Kelley M. Slayer, “Defense Primer: Directed-Energy Weapons,” Report 11882, Congressional Research Service, February 1, 2024, p. 1, https://sgp.fas.org/crs/natsec/IF11882.pdf.
[22] TRLs are a measurement system used by DOD to assess the maturity level of a particular technology. TRL 1 indicates basic principles are observed. TRL 2 indicates the technology concept is formulated. TRL 3 indicates experimental proof of concepts exist. TRL 4 indicates the technology has been validated in laboratory. TRL 5 indicates a component has been validated in a relevant environment. TRL 6 indicates the system has been demonstrated in a relevant environment. TRL 7 indicates the system prototype has been demonstrated in an operational environment. TRL 8 indicates the system is complete and approved. TRL 9 indicates the actual system is proven in its operational environment.
[23] “Top 100 Defense Companies for 2023,” *DefenseNews*, accessed May 1, 2024, https://people.defensenews.com/top-100/.
[24] Richard D. Fisher Jr., “U.S. Officials Confirm Sixth Chinese Hypersonic Manoeuvring Strike Vehicle Test,” *HIS Jane’s 360,* November 27, 2015, https://web.archive.org/web/20161105174036/http://www.janes.com:80/article/56282/us-officials-confirm-sixth-chinese-hypersonic-manoeuvring-strike-vehicle-test.
[25] Missile Defense Project, “DF-17,” *Missile Threat*, Center for Strategic and International Studies, February 19, 2020, last modified April 23, 2024, https://missilethreat.csis.org/missile/df-17/.
[26] U.S. Department of Defense, “Department of Defense Tests Hypersonic Glide Body,” Press Release, March 20, 2020, https://www.defense.gov/News/Releases/Release/Article/2119458/department-of-defense-tests-hypersonic-glide-body/.
[27] *See* Hearing, “U.S. and Adversary Hypersonic Capabilities,” House Armed Services Subcommittee on Strategic Forces, 118th Congress, U.S. House of Representatives, March 12, 2024, Washington D.C., https://armedservices.house.gov/hearings/str-hearing-us-and-adversary-hypersonic-capabilities.
[28] Id.
[29] Id.
[30] Id.
[31] Id.
[32] Id.

[33] "Hypersonic Weapons: DOD Should Clarify Roles and Responsibilities to Ensure Coordination across Development Efforts," Government Accountability Office, March 2021, https://www.gao.gov/assets/720/713180.pdf.
[34] Hearing, "U.S. and Adversary Hypersonic Capabilities."
[35] Id.
[36] Mark A. Milley, "National Military Strategy 2022," U.S. Department of Defense, October 27, 2022, https://www.jcs.mil/Portals/36/NMS%202022%20_%20Signed.pdf.
[37] Id.
[38] Id.
[39] Id.
[40] The People's Republic of China (PRC) has maintained a "No First Use" nuclear posture since 1964, indicating the PRC will not be the first to use nuclear weapons in a conflict. Hypersonic weapons can be leveraged as a conventional deterrence mechanism that falls beneath the threshold of triggering a nuclear response by China.
[41] Milley, "National Military Strategy."
[42] Brandon Weichert, "The Age of Big Powerhouse U.S. Navy Warships Is All Over Now," *The National Interest*, May 8, 2024. https://www.msn.com/en-us/news/world/the-age-of-big-powerhouse-us-navy-warships-is-all-over-now/ar-BB1m3So4?ocid=BingNewsSerp.
[43] Id.
[44] Noah Robertson, "The Pentagon Wants Industry to Transform Again to Meet Demand. Can It?" *DefenseNews*, February 20, 2024, https://www.defensenews.com/industry/2024/02/20/the-pentagon-wants-industry-to-transform-again-to-meet-demand-can-it/.
[45] Rebecca Wostenberg, Wilson Miles, and Jordan Chase, "Directed Energy Weapon Supply Chains: Securing the Path to the Future," The Emerging Technologies Institute, January 2024, p. 5, https://www.emergingtechnologiesinstitute.org/-/media/ndia-eti/reports/directed-energy-weapon-supply-chains/directedenergyweaponsreportdeeti.pdf?download=1?download=1.
[46] Shyam Sankar, "Why Increasing the Value of Defense Primes Is Good for the Country," *War on the Rocks*, May 1, 2024, https://warontherocks.com/2024/05/why-increasing-the-value-of-defense-primes-is-good-for-the-country/.
[47] Eric Lofgren, "Ratio of Sustainment to Acquisition Costs - Is Modernization Being Crowded Out?" *Acquisition Talk*, September 28, 2020, https://acquisitiontalk.com/2020/09/ratio-of-sustainment-to-acquisition-costs-is-modernization-being-crowded-out/.
[48] For detailed information on Norway and Japan, refer to Appendix A.
[49] Proposed Rule, "International Traffic in Arms Regulations: Exemption for Defense Trade and Cooperation Among Australia, the United Kingdom, and the United States," *Federal Register*, May 1, 2024, https://www.federalregister.gov/documents/2024/05/01/2024-08829/international-traffic-in-arms-regulations-exemption-for-defense-trade-and-cooperation-among. Additionally, and as another example, the Australian 2024 Defense Strategy prioritizes strengthening national defense capabilities and preserving Indo-Pacific security through a "whole of government" approach, which relies on procuring critical tools and technologies. Commonwealth of Australia, "National Defence Strategy," Australian Government, April 2024, https://www.defence.gov.au/about/strategic-planning/2024-national-defence-strategy-2024-integrated-investment-program. Moreover, an Australian 2016 Defense White Paper predicts hypersonic weapons capability by 2035, which influenced the U.S.-Australian Southern Cross

Integrated Flight Research Experiment program collaboration that is currently informing the prototype for the USAF's Hypersonic Attack Cruise Missile. Royal Australian Air Force, "SCIFiRE Hypersonics," accessed April 22, 2024, https://www.airforce.gov.au/ourwork/projects-and-programs/scifire-hypersonics; John Keller, "Advanced Hypersonics Munitions and Aircraft: Industry Shows It's Up to the Challenge," *Military+ Aerospace Electronics*, April 16, 2024, https://www.militaryaerospace.com/sensors/article/14310559/lockheed-martin-hypersonic-ruggedization-thermalmanagement-new-materials. Further, the U.K.'s "Integrated Review Refresh 2023" positions AUKUS as vital for countering coercion and maintaining international stability. His Majesties Government, "Integrated Review Refresh 2023: Responding to a More Contested and Volatile World," March 2023, https://assets.publishing.service.gov.uk/media/641d72f45155a2000c6ad5d5/11857435_NS_IR_Refresh_2023_Supply_AllPages_Revision_7_WEB_PDF.pdf. Through its Defense Command Paper 2023, the U.K. seeks science and technology superpower status by 2030, establishing a MOD "Team Hypersonics" to acquire hypersonic missile capability through a strategic mix of purchasing, collaborating, and developing technologies. Sean Monaghan, "Squaring the Triangle: Four Big Ideas from the Latest British Defense Review," Center for Strategic and International Studies, August 1, 2023, https://www.csis.org/analysis/squaring-triangle-four-big-ideas-latest-british-defense-review; His Majesty's Government, "Defence's Response To a More Contested and Volatile World," Defence Command Paper, July 2023, https://assets.publishing.service.gov.uk/media/64b55dd30ea2cb000d15e3fe/Defence_Command_Paper_2023_Defence_s_response_to_a_more_contested_and_volatile_world.pdf.

[50] Commonwealth of Australia, "2020 Force Structure Plan," Australian Department of Defence, July 1, 2020, https://www.defence.gov.au/about/strategic-planning/2020-force-structure-plan.

[51] Commonwealth of Australia, "Hypersonic Precinct to Supercharge Research," Australian Government Defense, February 11, 2022, https://www.defence.gov.au/news-events/news/2022-02-11/hypersonic-precinct-superchargeresearch. Additionally, Australian stakeholders involved in hypersonic development include the Defence Science and Technology Group, which conducts extensive research on scramjet technology; Hypersonix, which focuses on scramjet engines and advanced thermal protection materials; and partnership with the University of Queensland on the HyShot scramjet testing series. Hypersonix is also developing a hydrogen-fueled, zero-emission scramjet engine called Spartan for reusable space launch technology. Hypersonix collaborates with Kratos Defense to integrate the Zeus propulsion system into its DART Additive Engineering hypersonic aircraft, which utilizes single-use, high-temperature alloy scramjet technology.

[52] Tim Martin, "UK Launches Team Hypersonics in Bid to Eventually Develop 'Hypersonic Strike Capabilities at Pace,'" *Breaking Defense*, July 26, 2023, https://breakingdefense.com/2023/07/uk-launches-team-hypersonics-in-bid-to-eventually-develop-hypersonic-strike-capabilities-at-pace/#:~:text=BELFAST%20%E2%80%94%20The%20UK%20Ministry%20of,under%20a%20Team%20Hypersonics%20partnership. The U.K. Defense Science and Technology Laboratory collaborates with industry leaders such as BAE, Rolls Royce, and Reaction Engines to develop hypersonic technologies, including novel propulsion, thermal management, and advanced vehicle design. Several U.K. industries are actively involved in hypersonic technology, such as BAE systems, which develops propulsion systems and materials science for thermal protection; Rolls-

Royce, which contributes engines for hypersonic propulsion technologies; and Reaction Engines, which is developing the Strategic Air-Breathing Rocket Engine, a precooled hybrid hypersonic system.

[53] Seth G. Jones, "The U.S. Industrial Base Is Not Prepared for a Possible Conflict with China," Center for Strategic and International Studies, accessed May 1, 2024, https://features.csis.org/preparing-the-US-industrial-base-to-deter-conflict-with-China/.

[54] The Office of the Director, Operational Test and Evaluation, "AGM-183A Air-Launched Rapid Response Weapon (ARRW)," FY23 Report, accessed May 2, 2024, p. 265, https://www.dote.osd.mil/Portals/97/pub/reports/FY2023/af/2023arrw.pdf?ver=OBM6WqyRDHdmkkM9TRDBjA%3D%3D.

[55] Id.

[56] Congress likely zeroed FY24 ARRW RDT&E funding to concentrate resources on HACM. To convince Congress, the USAF downplayed ARRW's successful testing and up-played early testing failures in the program. The USAF desires HACM over ARRW because HACM is the hypersonic weapon needed for future operational missions. ARRW, on the other hand, is the weapon needed today for deterrence. The USAF likely did not want to risk future funding of HACM by continuing to pursue ARRW. The best solution is to keep both programs, but only buy a limited quantity of ARRWs. In 2023, the Congressional Budget Office estimated a production run of 300 ARRWs would have a unit cost of $15 million per missile and a program cost of $5.3 billion, including platform integration and 20 years of sustainment. For a production run of 100, each copy would cost $18 million, with a program cost of $2.2 billion. *See* "U.S. Hypersonic Weapons and Alternatives," Congressional Budget Office, January 2023, p. 4, https://www.cbo.gov/system/files/2023-01/58255-hypersonic.pdf, 2. Deterrence does not need to be upheld with mass and quantity. It can be upheld with the display of capability. The purchase of 100 ARRW should suffice. If ARRW were purchased to meet today's needs, the military services and DOD should align and prioritize programs to meet future needs.

[57] Sayler, "Hypersonic Weapons."

[58] Adam B. Peters, Dajie Zhang, and Samuel Chen, et al., "Materials Design for Hypersonics," *Nature Communications*, April 18, 2024, https://doi.org/10.1038/s41467-024-46753-3; Sayler, "Hypersonic Weapons."

[59] Guido Torres, Laura Delgado López, Ryan C. Berg, and Henry Ziemer, "Hypersonic Hegemony: Niobium and the Western Hemisphere's Role in the U.S.-China Power Struggle," Center for Strategic and International Studies, March 4, 2024, https://www.csis.org/analysis/hypersonic-hegemony-niobium-and-western-hemispheres-role-us-china-power-struggle.

[60] Peters, et. al., provides an exceptionally detailed breakdown of advanced and exquisite materials utilized in hypersonic systems in their article "Materials Design for Hypersonics," where they discuss the sourcing and manufacturing timeline delays associated with materials such as carbon carbon and the limitations of ceramics.

[61] Id.

[62] Courtney Albon, "Department of Defense Labs Face $5 Billion Infrastructure Shortfall," *DefenseNews*, January 24, 2022, https://www.defensenews.com/battlefield-tech/2022/01/24/department-of-defense-labs-face-5-billion-infrastructure-shortfall/.

[63] Test facilities are roughly divided into ground facilities and open-air ranges. The first category includes hypersonic wind tunnels, which can replicate the conditions that weapons will face when traveling at hypersonic speeds, at a cheaper cost, and with more accessible data collection than actual flight. According to DOD hypersonic and testing officials, wind tunnels are essential for testing parts and components, as well as validating designs before flight testing. The second category is open-air ranges, which can provide the space to accommodate the hypersonic speeds and monitor the tested system's flight path, impact, and performance. U.S. Government Accountability Office, "Hypersonic Weapons, " p. 25.

[64] National Academies of Sciences, Engineering, and Medicine, *Aeronautical Facilities: Assessing the National Plan for Aeronautical Ground Test Facilities*, (Washington, D.C.: The National Academy Press, 1994), p. 37, https://doi.org/10.17226/9088.

[65] Id.

[66] Sayler, "Hypersonic Weapons," p. 19.

[67] U. S. Government Accountability Office, "Hypersonic Weapons," p. 27.

[68] Wostenberg, et al., "Hypersonics Supply Chains Securing the Path to the Future," p. 22. In a meeting between the Secretary of Defense, other top DOD officials, and defense industry chief executive officers in February 2022, access to test facilities was one of the main concerns raised by industry regarding the development of hypersonic weapons, with participants emphasizing that without suitable testing facilities, the department will struggle to truly adopt a "test often, fail fast and lean" development approach. Courtney Albon and Joe Gould, "Top Pentagon Officials Met with Industry Executives about Hypersonics. What Comes Next?" *DefenseNews*, February 6, 2022, https://www.defensenews.com/industry/2022/02/04/top-pentagon-officials-met-with-industry-executives-about-hypersonics-what-comes-next/.

[69] Courtney Albon, "Pentagon Racing to Restore US Superiority in Hypersonics," *C4ISRNet*, January 6, 2023, https://www.c4isrnet.com/battlefield-tech/2023/01/06/pentagon-racing-to-restore-us-superiority-in-hypersonics/.

[70] Sayler, "Hypersonic Weapons," p. 13.

[71] "Senate Fiscal Year 2023 National Defense Authorization Act Bill Report," Senate Armed Services Committee, p.144, https://www.armed-services.senate.gov/imo/media/doc/fy23_ndaa_bill_report.pdf.

[72] "Future of Defense Task Force Report 2020," House Armed Services Committee, September 23, 2020, p. 37, https://houlahan.house.gov/uploadedfiles/future-of-defense-task-force-final-report-2020.pdf.

[73] Sayler, "Defense Primer."

[74] Id.

[75] John Grady, "Iran Has Put Middle East Into 'Convergence of Crises,' CENTCOM Commander Tells Senate," *USNI News*, March 7, 2024, https://news.usni.org/2024/03/07/iran-has-put-middle-east-into-convergence-of-crises-centcom-commander-tells-senate.

[76] Id.

[77] Id.

[78] Government Accountability Office, "Directed Energy Weapons: DOD Should Focus on Transition Planning," GAO-23-105868, April 17, 2023, https://www.gao.gov/products/gao-23-105868

[79] Id.

[80] The HEL consists of a high-energy laser mounted on a tactical vehicle, along with a control system for target acquisition and tracking. The HEL system utilizes a solid-state laser technology capable of generating a powerful beam to rapidly engage and destroy airborne targets, and offers several advantages over traditional kinetic weapons, including precision targeting, speed of engagement, and reduced logistical burden due to eliminating ammunition resupply needs. Andrew Feickert, "U.S. Army Weapons-Related Directed Energy Programs: Background and Potential Issues for Congress," Report 45098, Congressional Research Service, February 12, 2018, https://crsreports.congress.gov/product/pdf/R/R45098.
[81] Ronald O'Rourke, "Navy Lasers, Railgun, and Gun-Launched Guided Projectile: Background and Issues for Congress," Report 44175, Congressional Research Service, February 26, 2021, https://crsreports.congress.gov/product/pdf/R/R44175/69.
[82] Michael E. Davey, "The Airborne Laser Anti-Missile Program," Congressional Research Service, RL30815, February 18, 2000, https://congressionalresearch.com/RL30185/document.php?study=The+Airborne+Laser+Anti-Missile+Program.
[83] Wostenberg, et al., "Directed Energy Weapon Supply Chains," p. 5.
[84] U.S. Government Accountability Office, "Directed Energy Weapons."
[85] Mark Neice and Rebecca Wostenberg, "Securing Directed Energy Weapon Supply Chains," *National Defense*, February 2, 2024, https://www.nationaldefensemagazine.org/articles/2024/2/2/emerging-technology-horizons-securing-directed-energy-weapon-supply-chains.
[86] Wostenberg, et al., "Directed Energy Weapon Supply Chains," p. 5.
[87] Robertson, "The Pentagon Wants Industry to Transform Again to Meet Demand."
[88] Neice and Wostenberg, "Securing Directed Energy Weapon Supply Chains."
[89] Lofgren, "Ratio of Sustainment to Acquisition Costs."
[90] DEWs, including HELs and HPMs, are transforming modern defense capabilities. Given ongoing conflicts, DEWs provide crucial non-kinetic solutions to counter drones, projectiles, and other threats while conserving conventional munitions. Lasers are useful for engaging fast-moving targets within line-of-sight, such as destroying aerial or missile threats to ships, a base, or ground forces. HPMs are useful for disrupting electronic systems, making them especially useful against military equipment, drones, and robotic systems. James Black, "Directed Energy: The Focus on Laser Weapons Intensifies," *RAND Corporation*, January 25, 2024, https://www.rand.org/pubs/commentary/2024/01/directed-energy-the-focus-on-laser-weapons-intensifies.html.
[91] For detailed information on Japan and Israel, refer to Appendix B.
[92] U.S. Department of Defense, "Department of Defense Fiscal Year (FY) 2024 Budget Estimate," March 2023, https://comptroller.defense.gov/Portals/45/Documents/defbudget/fy2024/budget_justification/pdfs/03_RDT_and_E/OSD_PB2024.pdf.
[93] Wostenberg, et al., "Directed Energy Weapon Supply Chains."
[94] Commonwealth of Australia, "2020 Force Structure Plan."
[95] Australian Government Defence, "Government Announces Most Significant Reshaping of Defence Innovation in Decades to Boost National Security," Press Release, April 28, 2023, https://www.minister.defence.gov.au/media-releases/2023-04-28/government-announces-most-

significant-reshaping-defence-innovation-decades-boost-national-security. Australia also established the Southern Hemisphere's most extensive DEW testing range in Melbourne, a A$13 million partnership with QinetiQ for laser development, and successful demonstrations of counter-drone systems like Fractl, further underscore this commitment. Sean Byrne, "Australia Wants to Build a Laser That Can Stop a Tank. Here's Why 'Directed Energy Weapons' Are on the Military Wishlist," *UNSW Sydney*, May 2 2023, https://www.unsw.edu.au/newsroom/news/2023/05/australia-wants-to-build-a-laser-that-can-stop-a-tank--here-s-wh#:~:text=stop%20a%20tank.-,Here's%20why%20'directed%20energy%20weapons'%20are%20on%20the%20military%20wishlist,ammunition%20promised%20by%20laser%20weapons.

[96] U.K. Ministry of Defence, "Advanced Future Military Laser Achieves UK First," Press Release, March 21, 2024, https://www.gov.uk/government/news/advanced-future-military-laser-achieves-uk-first.

[97] Wostenberg, et al., "Directed Energy Weapon Supply Chains."

[98] Australia's DEW initiatives drive economic growth within its defense industry. In addition to the A$3.4 billion ASCA program imitative, AIM Defence produces the drone Fractl, which runs about A$650,000 per unit. Sean Carberry, "Just In: New Counter-Drone Weapon Works from a Distance," *National Defense Magazine*. November 8, 2023, https://www.nationaldefensemagazine.org/articles/2023/11/8/ new-counter-drone-weapon-works-from-a-distance. Partnerships with companies like QinetiQ and Electro Optic Systems also foster technological innovation, job creation, and potential export opportunities. In April 2023, the Defence Science and Technology group announced a $13 million deal with U.K. defense technology company, QinetiQ, to develop a prototype defensive laser. O'Byrne, "Australia Wants to Build a Laser That Can Stop a Tank." Additionally, Australia's supply of critical materials like rare earth elements, manganese, and lithium supports DEW development and strengthens supply chains. The U.K.'s DEW initiatives also stimulates economic growth through industry partnerships and technological innovation. The £100 million DragonFire program developed by an industry partnership between the Minority Business Development Agency, Leonardo, and QinetiQ, was expensive to develop, but can yield financial savings overall. DragonFire is now estimated to cost approximately £10 ($12–13) per shot, and 10 seconds of sustained firing is the equivalent of running a home heater for an hour. By comparison, current estimates of U.S. and U.K. defensive conventional munitions used to eliminate incoming Houthi projectiles fired at Western vessels in the Red Sea cost approximately $2 million per missile. Stuart Dee and James Black, "Directed Energy Dilemmas: Industrial Implications of a Military-Technological Revolution," *RAND Corporation*, February 20, 2024, https://www.rand.org/pubs/commentary/2024/02/directed-energy-dilemmas-industrial-implications-of.html. Finally, the U.K.'s beam control and manufacturing expertise ensures a resilient DEW supply chain, benefiting the U.K. and its allies. The U.K. MOD is collaborating with U.S. defense industrial base members to develop HEL technology and exchange component technology. Other energy storage collaborations with the U.S. drive advances in the defense sector, such as Raytheon U.K. delivering its first HEL weapon system tested in the U.K., the 15-kilowatt laser was a collaboration between RTX, Raytheon U.K, and the U.K. MOD's Land Demonstrator program. RTX, "Raytheon UK Set To Receive and Integrate U.K.'s First Laser Weapon System in October," Press Release, September 13, 2023,

https://www.rtx.com/news/news-center/2023/09/13/raytheon-uk-set-to-receive-and-integrate-uks-first-laser-weapon-system-in-octobe.

[99] Wostenberg, et al., "Directed Energy Weapon Supply Chains."

[100] Proposed Rule, "International Traffic in Arms Regulations."

[101] Wostenberg, et al., "Directed Energy Weapon Supply Chains," p. 33.

[102] Kelley M. Sayler, Andrew Feickert, and Ronald O'Rouke, "Department of Defense Directed Energy Weapons: Background and Issues for Congress," Report 46925, Congressional Research Service, August 22, 2023, p. 17, https://sgp.fas.org/crs/weapons/R46925.pdf.

[103] Emily Johnson, "The Role of Directed Energy Weapons in Modern Warfare," *Strategic Studies Quarterly* 42, no. 2 (2020): pp. 78-92.

[104] Id.

[105] Michael Brown, "Challenges and Opportunities in the Operational Use of Directed Energy Weapons," *Defense Technology Review* 15, no. 4 (2019): pp. 102-115.

[106] Id. DEWs are also susceptible to atmospheric conditions that can affect beam propagation and effectiveness. Factors such as humidity, fog, dust, and smoke can degrade beam quality and reduce engagement range, limiting the operational effectiveness of DEWs in adverse weather conditions or environments. Addressing these environmental considerations requires ongoing research and development to improve DEW performance in varied operational scenarios. And adversaries may rapidly develop countermeasures to mitigate the effectiveness of DEWs or deploy their own counter-DEW systems to neutralize incoming energy beams. Countermeasures could include reflective coatings, decoys, or jamming techniques designed to disrupt or deflect DEW attacks. Furthermore, the proliferation of counter-DEW technologies poses a threat to friendly forces, requiring the U.S. military to develop counter-countermeasures and defensive strategies to maintain the advantage on the battlefield. Black, "Directed Energy."

[107] Sayler, "Defense Primer."

[108] Joseph Corso, "nLIGHT Announces Expansion of HELSI Contract Award to $171 Million for Development of 1 Megawatt Directed Energy Laser," Press Release, November 2, 2023, https://investors.nlight.net/news-releases/news-details/2023/nLIGHT-Announces-Expansion-of-HELSI-Contract-Award-to-171-Million-for-Development-of-1-Megawatt-Directed-Energy-Laser/default.aspx.

[109] Epirus, "Counter Electronics," website, accessed April 23, 2024, https://www.epirusinc.com/counter-electronics.

[110] When asked whether the government would benefit more by focusing on architecture standards than complete systems to allow for agile system improvements and support, one respondent remarked that it would likely improve the competitive industrial base. The respondent explained that down-selected industry participants would be more inclined to remain in the market to compete for future upgrades or support. A common architecture could also increase interest and compatibility with partners and allies. While not direct parallels, the current NATO 155mm artillery incompatibility issue emphasize the importance of common standards. *See* Sabine Siebold, "NATO Urges Common Standards and Curbs on Protectionism to Boost Artillery Output," *Reuters*, October 24, 2023, https://www.reuters.com/world/nato-urges-common-standards-curbs-protectionism-boost-artillery-output-2023-10-24/.

[111] Epirus, Twitter Post, 10:39 AM, December 5, 2023, https://twitter.com/epirus/status/1732062043757264904.

[112] Colin Demarest, Megan Eckstein, and Geoff Ziezulewicz, "Amid Red Sea Clashes, Navy Leaders Ask: Where Are Our Ship Lasers?" *Navy Times*, January 22, 2024, https://www.navytimes.com/news/your-navy/2024/01/22/the-us-navy-could-use-some-lasers-on-its-surface-fleet-right-now/; Jon Harper, "Pentagon's Directed Energy Guru Sees 'Uncomfortable Choices' Ahead for Military Commanders," *DefenseScoop*, January 23, 2024, https://defensescoop.com/2024/01/23/directed-energy-weapon-pentagon-peterkin-uncomfortable-choices/.

[113] "nLight Agrees Megawatt Laser Weapon Deal," Business News, Optics.org, November 7, 2023, https://optics.org/news/14/11/9.

[114] This is in line with recent comments from the Undersecretary for Research and Engineering, Heidi Shyu, when she said, "[i]f you really want to go fast, you really need to take advantage of something that's already there that you can modify and get additional capability not originally designed in the system." Sean Carberry, "Iranian Attack Highlights Need for Integrated, Layered Missile Defense," *National Defense*, April 16, 2024, https://www.nationaldefensemagazine.org/articles/2024/4/16/iranian-attack-highlights-need-for-integrated-layered-missile-defense. Without a deployed system with a common architecture, the industry is left to rely on research and development efforts that suffer from inconsistent funding and potential cancelation. Field site visit comments confirmed the Emerging Technology Institute's observation that lack of a clear demand signal and DEW strategic vision limit the industrial base to fielding a small number of systems with long lead times.

[115] Id. at 16.

[116] Henry "Trey" Obering III, "Directed Energy Weapons Are Real . . . And Disruptive.," *PRISM Security Studies Journal* 8, no. 3 (January 1, 2020): p. 38.

[117] Wostenberg, et al., "Directed Energy Weapon Supply Chains," p. 16.

[118] Id.

[119] Ron Wilson, "Test-Driven Hardware Development: True or False?," *Design and Ruse*, February 22, 2018, https://www.design-reuse.com/articles/43629/test-driven-hardware-development-true-or-false.html.

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[121] The School's Observatory, "Starship," website, *Liverpool John Moores Univerity*, accessed April 24, 2024, https://www.schoolsobservatory.org/learn/eng/exp/starships.

[122] Wostenberg, et al., "Directed Energy Weapon Supply Chains," p. 28.

[123] "Directed Energy Weapons," Government Accountability Office.

[124] Wostenberg, et al., "Directed Energy Weapon Supply Chains."

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[129] Wostenberg, et al., "Directed Energy Weapon Supply Chains."

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