Prepared Statement of
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Thank you Co-Chairs, members of the Commission, and staff for the opportunity to testify today on this very important topic. The rapid pace at which China is developing advanced weaponry has critical implications for military and diplomatic strategy, as well as the U.S. military's own research, development, and acquisition (RDA) strategy.

I. Rise of Chinese Advanced Military Technology

In 1991 Chinese leadership watched in shock as the United States military decimated the air defenses of the Iraqi military. The formidable Soviet-based weapons technology used by the Iraqis were the same systems at the heart of Chinese military capability. This U.S. military might was brought to China's doorstep during the Taiwan crisis of 1995-1996, when in 1996 two U.S. carrier strike groups were deployed into the region, and the USS Nimitz was sailed through the Taiwan Straits. While the Chinese government was forced to back down in this particular crisis, it sparked a strong determination by the Chinese that they would never be strong-armed again by the U.S. or any other military power, particularly in their home region. Thus began a decades-long, highly coherent strategy on the part of the Chinese government to make modernization of their military a top national priority.[2]

The initial phase of that modernization focused on "catching up", albeit in large numbers. To fight a regional war, China pursued a strategy of "good enough", in which it developed modern capabilities aligned with most elements of U.S. military capability. For example by leveraging relatively modest advances in missile technology, China has a large arsenal of ballistic missiles that can threaten U.S. carrier strike groups (CSGs) and regional bases and allies.[3] Likewise the J-20 fighter, while no match head-to-head with advanced U.S. aircraft like the F-22 and F-35, is still formidable and may ultimately be fielded in large enough numbers to overwhelm U.S. planes in a regional battle.[4]

But now China is heading into the next phase of its modernization strategy. Instead of simply relying upon overwhelming the U.S. with "catch-up" capabilities in large numbers, China is now developing weapons in key areas that may leapfrog the U.S, attempting to negate specific U.S.

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[1] The views and opinions expressed in this testimony are solely those of the author and do not reflect in any way those of any clients of the author or Fortitude Mission Research.
[2] Kazianis, Harry J., Eliot Pence, Daniel McCarthy, and Daniel L. Davis. "3 Chinese Weapons of War the U.S. Navy Should Fear." The National Interest. Web. 04 Feb. 2017.
[3] Kazianis, Harry J., Eliot Pence, Daniel McCarthy, and Daniel L. Davis. "Exposed: China's Super Strategy to Crush America in a War." *The National Interest*. Web. 04 Feb. 2017.
[4] Lockie, Alex. "How China's Stealthy New J-20 Fighter Jet Compares to the US's F-22 and F-35." *Business Insider*. Business Insider, 01 Nov. 2016. Web. 04 Feb. 2017.

strengths. This hearing is focusing on three of these research areas, hypersonics, directed energy, and space control.

Hypersonics is an extension of existing ballistic missile and cruise missile capability, but instead of saturating missile defenses with numbers, the speed and maneuverability of hypersonic weapons may make kinetic missile defenses obsolete.[5] Directed energy and space control target the current overwhelming U.S intelligence, surveillance, and reconnaissance (ISR) advantage. Both Desert Storm and the more recent campaigns in Afghanistan and Iraq demonstrated the importance of ISR, particularly space-based ISR, to U.S. military might. New capability in directed energy threatens U.S. sensor capabilities with blinding or damage, and space control systems threaten U.S. satellites themselves.[6]

As China pursues this aggressive advanced technology modernization strategy, it is important to consider the implications for U.S. policy and overall military effectiveness. This is not a simple prospect. Predicting the schedule of technology breakthroughs is daunting even for a program under one's own control, driven by the inherent risk of advanced research. This prediction is exponentially more challenging when guessing about someone else's research activities with only limited public insight available. The U.S. intelligence community should be commended for its technical depth and ability to put together any picture we have. That being said, there is an inherent risk of "mirroring" as we attempt to interpret intelligence data and public statements to make predictions of when certain Chinese advanced weapon capabilities will mature and be fielded. The risk emerges from the very different research approaches, constraints, and conditions of the Chinese military modernization program compared with similar U.S. military research activities today and in the past.

The caution I wish to present is that Chinese advanced weapon systems may mature at a much faster rate than any current predictions. There is a serious threat that a breakout new weapon may negate large elements of U.S. military capability and subsequently the balance of power in the Pacific region. At the same time, the high risk associated with this technology makes predictions of the future highly uncertain. This combination of severe consequences with high uncertainty merits completely new strategic thinking about what the U.S. response should be. In the remainder of this testimony, I will first provide some background on the key technology enablers in some of the weapon capabilities of interest. Then I will describe some of the conditions that are driving accelerated Chinese weapon technology develop, and I will conclude by discussing some of the implications for the U.S. military with recommendations for actions that the Congress can take to mitigate the risks.

II. Advanced Weapon Enabling Technologies

The thought of advanced weapons technologies may conjure many different impressions among those not involved in the development of such systems. Many people immediately think about the platform or complete system. For example when China launched its first taikonaut into space

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[5] Macdonald, Cheyenne. "Chilling Air Force Report Warns Russia and China's Hypersonic Missiles 'may Endanger the United States'." *Daily Mail Online*. Associated Newspapers, 01 Dec. 2016. Web. 04 Feb. 2017.

[6] Gady, Franz-Stefan. "Should the US Fear China's New Space Weapons?" *The Diplomat*. The Diplomat, 23 Oct. 2015. Web. 05 Feb. 2017.

in 2003[7], many scoffed. Their rockets and space vehicles were arguably not much more advanced than what the U.S. flew during the Mercury program in the 1960s. “Spacecraft”, “fighter”, “ballistic missile” are all tangible system technologies but do not capture the know-how and enablers that lead to the capability. We focus on technology at this level because it is tangible and understandable to a layman.

In analysis I have conducted for various purposes and sponsors, including an Office of the Secretary of Defense (OSD) study on disruptive emerging technology in 2010, I consider three categories of enablers. These may be identified by isolating barriers to developing a particular weapon capability. The first of these essential enablers is fundamental scientific knowledge. Is there some fundamental physical phenomenon, biological discovery, or mathematical theorem that is essential to the weapon technology? The next category of enablers is the need for a critical component or material. Does the weapon technology require a new semiconductor chip, computing device, or power supply? Likewise does it depend upon the ability to mine, refine, or process unique materials? Finally, are there more skill-oriented technology enablers that I refer to informally as “ilities”? These very abstract, difficult-to-quantify capabilities could nevertheless turn out to be the most important barriers or enablers. They span a wide range of disciplines but include skills and tools such as advanced manufacturing capability, metrology or the ability to make very precise measurements, modeling and simulation, and testing techniques and facilities. An important note about this third category that I will return to later in the testimony is that the only way to obtain “ilities”, shy of being taught, is through trial and error. Physically obtaining a copy of a system does not illuminate how it was built. Conversely, any country willing to expend time and treasure can overcome this barrier.

Now before examining how these categories of enabling technology apply to the topic of this panel, directed energy, it is useful to define what is meant by this technology domain. The goal of directed energy is to affect a target at the speed of light. Unlike a kinetic weapon, which must be propelled toward the target, a beam of directed energy transits to the target for all practical purposes instantaneously. This has tremendous advantage against very fast or highly maneuverable targets. Also the effects that can be achieved by directed energy can be highly variable and tailorable to a mission objective. Directed energy effects range from physical destruction, to damage of a sensor or other mission function, to much more subtle, reversible disruption, whereas kinetic weapons typically are limited to violent destruction.

Types of directed energy fall into three main classes, high-energy lasers, high-power microwave, and particle beams. All use different core technology and phenomena and have different effects and strengths and weaknesses, but they share the characteristic of near-instantaneous propagation and non-kinetic effect. Most laser weapons, or HELs, rely upon transferring energy into the physical structure of a target, generating large amounts of heat and ultimately causing structural failure. High-power microwave weapons, or HPMs, beam intense electro-magnetic fields at a target, not unlike a microwave oven. However unlike a microwave oven, or an HEL for that matter, HPMs do little to heat the structure but rather induce high currents into electronics inside the target. These currents can disrupt the electronic circuits to disable them or even physically

[7] Calmes, Ben. "China Space Program: Timeline and Brief History From Operation Paperclip to Project 921 and the Shenzhen Spacecraft." *China Space Program: Timeline and Brief History From Operation Paperclip to Project 921 and the Shenzhen Spacecraft*. Sinomania, 2005. Web. 11 Feb. 2017.

destroy semiconductor devices. Particle beams are the most exotic and least mature directed energy technologies but if perfected are perhaps the most dangerous. When a particle beam strikes a target, it generates additional highly-energetic particles and electro-magnetic fields inside the cavity of the target. The resultant effect on the electronics of the target is similar to HPM, but unlike HPM, it is nearly impossible to shield a target from particle beam effects.

To illustrate how the categories of enabling technology apply to directed energy, consider the key elements of an HEL weapon. There are three main system elements to any HEL: The laser itself generates the intense source of light; an electrical power supply must be capable of driving the laser with powerful, short bursts of energy; and a beam director steers the beam onto the target while simultaneously correcting for atmospheric effects. Each of these sub-systems is enabled by critical technologies in the three categories described above, but in the interest of time, this testimony will focus on the laser source itself as an example.

There are several key areas of fundamental scientific knowledge required just for the HEL laser source. For purposes of this testimony, I will spare you a lecture on basic laser physics. However there are many elements of fundamental knowledge that are required to design an HEL. These include physical optics to design an optical cavity, chemistry and atomic physics to select and produce a laser gain medium, semiconductor physics and engineering to produce diode lasers for pump light, thermodynamics to control excessive waste heat, and high-voltage electrical engineering to design the diode laser drive circuits. In addition to specialty knowledge in each of these areas, one must also know how to combine them to make an HEL. While this may sound daunting, each of these areas of science are widely accessible globally, and as will be discussed later in this testimony, even research on design of full HEL systems is widely available in the public domain.

Next consider critical materials and components. Early attempts at HEL by the U.S. used gas lasers. For example the Airborne Laser or ABL was to use a Chemical Oxygen Iodine Laser or COIL, which was a gas laser system[8]. Ultimately the gas-based laser proved to be too large even for a Boeing 747, so almost all current HEL research is focused on solid-state laser designs.

The key enabling component of a solid-state HEL is a laser crystal. These crystals absorb pump light and generate and amplify light at the laser wavelength to create the output beam. While there are many options, the best candidate is arguably different types of materials doped with the element neodymium. Neodymium-doped crystals are used in solid-state lasers ranging from research lasers to medical lasers to high-power industrial lasers and in HEL weapon-class lasers. A major challenge in producing solid-state laser materials is not just the obtaining of the neodymium but also the precise, highly controlled growth of large, very pure crystals. Note that while critical to solid-state lasers, neodymium is in even higher demand for use in very powerful industrial magnets.

Another critical component technology for HEL laser sources, especially for tactical systems for which size and mass of the laser are critical, are pump diode lasers. These must be designed with certain optical wavelength and beam quality characteristics, as well as being electrically

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[8] "Airborne Laser System (ABL) YAL 1A." Airforce Technology. N.p., n.d. Web. 12 Feb. 2017. <http://www.airforce-technology.com/projects/abl/>.

efficient. It is helpful if they are also inexpensive, as they are needed in large quantity for an HEL.

Much of the final abstract enabler critical technology category centers on scaling laser power to weapons-suitable levels, while keeping size, weight, and power of the system manageable enough for tactical use. This begins with knowing how much laser power is necessary to serve as a weapon. This knowledge is obtained through controlled research into how laser light interacts with different material types and extends to trial-and-error measurements of weapon lethality using prototype laboratory systems.

Scaling HEL to achieve these required power levels is largely driven by an ability to model heat flow in laser media and by producing crystals of significant enough purity and uniformity so that waste heat is minimized and easily removed. An efficient waste heat removal system must also be designed.

Supporting systems and techniques must be developed to keep components meticulously clean, as one microscopic speck of dust may burn up and mar the components in a way that degrades performance or even causes irreparable damage. Components must be assembled with careful techniques that avoid even the slightest scratches and abrasions, as these will scatter stray light and again cause degraded performance or damage.

Testing, characterizing, and calibrating the HEL requires special facilities and equipment. One cannot simply point a laser designed to burn holes in missiles into a commercial power meter to measure how well it is working without destroying the test apparatus. Very precise measurements of beam quality are needed well beyond the capability of commercial instruments to ensure laser lethality.

III. Chinese Access to Critical Enablers

Given this brief survey of critical enabling technologies, let us now take a look at how Chinese resources and actions might align with the capability to develop HEL weapon technology. Are there are any fundamental barriers to prevent China from developing HEL weapon technology?

Knowledge Base

The fundamental physics behind HELs is very well-known. Much of the work in this area is conducted by academic institutions with an objective of publishing research. A simple Google Scholar search on as specific a topic as "high energy laser cavity design" generates 1240 unique publication just since 2013. Adding the word "weapon" reduces the number of results to *only* 152. Some of these are entire books[9], and many are published by the U.S. military[10]. Before jumping to the conclusion that it is irresponsible for the military to publish these types of articles, it is important to note that there is an even greater number of HEL publications with the term

[9] See for example Zohuri, Bahman. "Laser Technology." Directed Energy Weapons. Springer International Publishing, 2016. 27-33.

[10] See for example Zamora, Jovan, et al. Comprehensive System-Based Architecture for an Integrated High Energy Laser Test Bed. NAVAL POSTGRADUATE SCHOOL MONTEREY CA DEPT OF SYSTEMS ENGINEERING, 2015.

"industrial" added, 559 since 2013 to be exact. In a project for a private client, we identified at least 19 companies globally that either manufactured lasers of a class scalable to an HEL weapon system or that produced key components required for HEL weapons for commercial manufacturing applications such as welding and metal cutting. Most of these are not U.S. companies.

Clearly there is no shortage of fundamental knowledge in the public domain for core laser source technology, and while not investigated in detail, the other system elements show similar trends. For example the most challenging aspect of beam direction is correction of atmospheric disturbances using a technique known as "adaptive optics".[11] While developed decades ago in secret for HEL applications, the research field is dominated today by the astronomy community and even has applications as diverse as ophthalmology.

China is well-positioned to take advantage of this wealth of publicly available knowledge, largely by developing technical talent around the world, particularly within the U.S. Based upon data from the 2015/16 academic year[12], China was the number one country for sending international students to U.S. universities. They accounted for 328,547 out of a total of 1,043,839 international students or 31.5%. Of these numbers, many study physics. Since 1990 about half of U.S. physics graduate students have been international[13], which based upon general trends would mean over 15% of U.S. graduate physics degrees went to Chinese students. China is transferring this capability back to its own universities. According to at least one international ranking, 6 out of the top 200 universities for physics in 2016 were in China.[14] With the volume of HEL physics knowledge in the public domain, there is little question that China possesses the intellectual capital to exploit it.

Components and Materials

Next consider the availability of key components and material with a special focus on the laser gain medium. Development of materials in general and crystal growth in particular is as much an art as science, requiring an intense long-term commitment. This is driven by the sensitivity of crystal growth to a wide range of unpredictable and difficult-to-control parameters. China is particularly well-positioned to conduct this type of research through their ability to massive amounts of resources. As just discussed, China has a substantial pool of scientific talent to draw upon. It also has the relative financial resources needed to conduct the massive research projects required to develop laser materials. Chinese defense spending is projected to grow to USD 233 billion by 2020, and this spending goes much further than the equivalent spending in the U.S. If one considers the ratios of national per capita incomes[15], a U.S. defense engineer making

[11] See for example Davies, Richard, and Markus Kasper. "Adaptive optics for astronomy." Annual Review of Astronomy and Astrophysics 50 (2012): 305-351.
[12] "International Students in the United States." International Students in the United States. Institute of International Education, 2016. Web. 12 Feb. 2017.
[13] Mulvey, Patrick J., and Starr Nicholson. "Trends in Physics PhDs." Focus on (2014): American Institute of Physics, Feb. 2014. Web. 12 Feb. 2017.
[14] "ARWU World University Rankings 2016 | Academic Ranking of World Universities." ShanghaiRanking Consultancy, 2016. Web. 12 Feb. 2017. <http://www.shanghairanking.com/index.html>.
[15] "GDP per Capita, PPP (current International $)." World Bank, 2016. Web. 12 Feb. 2017. <http://data.worldbank.org/indicator/NY.GDP.PCAP.PP.CD>.

$100,000 per year would cost only about $20,000 in China. With the financial resources and human capital at its disposal, China is perfectly positioned to conduct massive materials development campaigns. In general, the U.S. has been reluctant to put further the sustained commitment necessary for material maturation.

Indeed, not only does China have the resources to become a world powerhouse in materials research, it has demonstrated the intention, which has been recognized by the international scientific community.[16] It should be noted that development of advanced materials is also a key enabler for other elements of an HEL system, such as components for high-power energy storage and conditioning, and also for hypersonics, in the structural materials needed to withstand the thermomechnical stress of hypersonic flight.

Another key enabler is the availability of raw materials. Once again, not only does China have easy access to key materials, but it in fact dominates. Neodymium, described earlier as one of key elements enabling solid state lasers, is one of the rare earth elements on the period table. As has been noted by many organizations, including the U.S. Congress[17], China dominates the global market for mining and refining rare earths and specifically neodymium. China is estimated to possess approximately half of the global reserves but mines and refines over 90% of global annual production[18].

China has also demonstrated a willingness to control rare earth markets. There is economic as well as strategic advantage to China in controlling the global availability of these minerals. If too much ore is sold globally, prices drop to levels that make production unprofitable, but if supplies are limited too much, global prices could rise to a level that encourages other countries to increase production. China is currently in the process of greatly limiting production, mainly to combat rampant illegal mining.[19] Only time will tell what the economic and availability implications of this move are. In the meantime, whether it is their primary motivation or not, China will control most of the world's supply of a material critical to HEL.

Abstract Enablers / "Ilities"

Finally let us consider the soft skills that contribute to development of HEL weapons. This is an area in which the U.S. has a commanding lead by virtue of time. U.S. research in HEL dates back almost to the dawn of the laser in the 1960s, whereas serious Chinese HEL research is not much more than a decade old. Much of that U.S. advantage has gone into robust thermal and

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[16] "China's Mark on Materials". *Nature Materials* **15**, 688 (2016).

[17] "Committee Unanimously Approves Bill to Strengthen and Advance National Minerals Policy." *House Committee on Natural Resources*, 20 July 2011. Web. 13 Feb. 2017. <http://naturalresources.house.gov/newsroom/documentsingle.aspx?DocumentID=252844>.

[18] "Neodymium." *Neodymium | Materials Information System*. European Commission, 7 Apr. 2016. Web. 13 Feb. 2017. <https://setis.ec.europa.eu/mis/material/neodymium>.

[19] Aspa, Jocelyn. "China Puts Annual Limit on Rare Earth Production." *Investing News Network*. Dig Media Inc., 18 Oct. 2016. Web. 13 Feb. 2017. <http://investingnews.com/daily/resource-investing/critical-metals-investing/rare-earth-investing/china-puts-limit-on-rare-earth-production/>.

lethality modeling, backed up by many person-years of data collection in laboratory and field experiments.

While it will be a challenge for China to make up this lost time, it has two major advantages. Development of these abstract enablers is largely a cycle of experimentation and modeling. Experiments provide initial experience and generate large quantities of data. Data help refine and validate computer models, which can in turn be used to perform virtual experimentation. This simulation-based experimentation focuses real-world experimentation, leading to more successes and greater efficiency, generating much more data, and so on in a virtuous cycle.

China's two major advantages lie in the steps of this cycle. First it has incredible computational capabilities brought about by a combination of globalization and their own internal investments. China does not dominate the U.S. in computational capability, but it has reached parity. TaihuLight became the world's most powerful supercomputer last year, and China achieved this using all indigenous components, architecture, and operating system[20]. While this advance does not put China significantly ahead of the current U.S. computational capability, it is significantly ahead of U.S. capability in the early decades of HEL research. This will allow China to bypass much of the need to prototype and experiment, cutting off significant development time.

On the topic of experimentation, their posture here represents China's other great accelerator. While not necessarily a model to be emulated, the Chinese military has shown a proclivity to take risks and short-change environmental and safety measures for expediency. It has adopted an experimental strategy that favors many frequent, incremental tests over the U.S. model of much fewer major milestone tests. While this Chinese approach may produce occasional dramatic failures, it also enables very rapid learning and happens to be the model practiced by Silicon Valley entrepreneurs for agile software development.

China has pulled these trends together with a demonstrated intent of streamlining and integrating its military development and operations. From a political and bureaucratic perspective, the Chinese military's speed that arises from suppression of dissent and aggressive, high-risk development has often been offset by deep rifts between its services. However, recent moves to re-organize the military have beaten down these barriers and reduced internal corruption in the process.[21] There is a high likelihood that this streamlining alone will become a major enabler to faster development.

[20] Vincent, James. "Chinese Supercomputer Is the World's Fastest - and without Using US Chips." *The Verge*. The Verge, 20 June 2016. Web. 13 Feb. 2017. <http://www.theverge.com/2016/6/20/11975356/chinese-supercomputer-worlds-fastes-taihulight>.

[21] Cordesman, Anthony H., Joseph Kendall, Daniel L. Davis, Leon Hadar, and Daniel McCarthy. "China's Evolving Military Strategy and the Reorganization of the People's Liberation Army." *The National Interest*. The National Interest, 29 Aug. 2016. Web. 13 Feb. 2017. <http://nationalinterest.org/blog/the-buzz/chinas-evolving-military-strategy-the-reorganization-the-17508>.

IV. Implications for the U.S. Military

Given these technology enablers and trends, there are several major implications for the U.S.

Directed Energy Weapons Strategically Aligned against U.S. Military Strengths

The most direct implication is the actual military threat. A successful directed energy weapon is an asymmetric counter to key U.S. strengths. The U.S. views directed energy as a speed-of-light interceptor to counter adversary weapons, most notably the ballistic missiles that threaten U.S. aircraft carriers and other capital assets. While the Chinese may see a long-term need for a parallel missile defense capability, the foreseeable reality is that the U.S. will not rely upon ballistic missiles as a key offensive weapon[22].

Instead the U.S. depends upon information dominance and precision weapon targeting as its key strategic force multipliers. These capabilities are particularly vulnerable to a directed energy countermeasure. While U.S. HEL capability must seek to burn holes in missile bodies, Chinese HEL weapons can have equal mission effectiveness by simply blinding or damaging a guided missile seeker or satellite sensor. Optical seekers are particularly vulnerable to HELs, and while radio frequency (RF) seekers may themselves be harder to damage with an HEL, their radomes are not. A seeker radome with a large hole in the middle makes a missile aerodynamically unstable and ruins its guidance capability. This produces a physics-based asymmetry in which a Chinese HEL with much less net power than a U.S. counterpart system, may still have the same or greater mission effectiveness.

It should also be noted that a mature Chinese directed energy capability potentially leapfrogs future U.S. military strategy. For example, one of more innovative future U.S. military strategies replaces small numbers of monolithic, high-value platforms with large numbers of swarming, expendable capabilities[23]. This approach can potentially impose an unsustainable cost on an adversary if he is forced to counter these low-cost platforms with expensive, long-range interceptor missiles. In addition, large enough swarms can completely saturate a kinetic air defense system by forcing the adversary to expend all of his missiles before all the attacking platforms are destroyed.

However if the adversary has an effective directed energy weapon, the incremental cost per kill is minuscule, and the number of available shots is essentially limitless. Thus, directed energy weapons may negate advanced U.S. military concepts before they are even fielded.

No Fundamental Barriers, Difficult to Deter

I hope that this testimony thus far has presented a compelling case, at least for HEL, that there are no serious fundamental barriers to China eventually obtaining an effective directed energy

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[22] The U.S. avoidance of ballistic missile weapons technology is driven by Cold War treaties with the former Soviet Union. While China is not a party to these restrictions, an action by the U.S. to violate these treaties to address the China threat would be globally destabilizing.

[23] Limer, Eric. "Watch the Navy's LOCUST Launcher Fire Off a Swarm of Autonomous Drones." *Popular Mechanics*. Hearst Communications, Inc., 24 May 2016. Web. 13 Feb. 2017. <http://www.popularmechanics.com/military/weapons/a21008/navy-locust-launcher-test-2016/>.

weapon system. To summarize, they have access to sufficient fundamental knowledge and the intellectual capital to understand and exploit it, and they have access to all the necessary components and materials, arguably leading the U.S. in development of key laser crystals. Their remaining hurdles all lie within the category of abstract enablers, specifically associated with scaling power and achieving tactically relevant packaging. As discussed, the only fundamental barrier to learning these abstract elements and achieving a practical weapon capability is effort – time, will, and money.

Therefore, if the last missing ingredient is effort, this is very difficult to deny or deter. Export control contributes little benefit, since at least as it is traditionally practiced, it only prevents the international sale of hardware and deliverable system software, tangible things that can be defined by key words. Procedures and other supporting skills are not typically captured in export control lists.

It is also important to note that attempting to deter effort can often lead to unintended consequences. While not necessarily as applicable to directed energy, I have conducted analyses of export policy as applied to other weapon technology and discovered that U.S. export control restrictions may actually motivate other countries to develop their own indigenous capability. Only a very carefully orchestrated, strategically crafted campaign of incentives and disincentives can effectively deter effort by influencing will.

Head-to-Head Directed Energy Arms Race is High Risk

A directed energy arms race is likely to be a losing proposition for the U.S. This relates partially to the recurring theme that the limiting factor is effort, and as discussed previously, China has more than enough financial and human resources to outlast the U.S. in a direct battle of wills. Even given a national-level priority, the U.S. is likely to maintain only a marginal lead and at great cost.

Part of this risk is driven by the inherent remaining technical challenges to make directed energy a reliable weapon capability. Power scaling, size reduction and packaging, system reliability, and overall cost still remain large questions for the U.S. as well as China. Directed energy may also be very susceptible to certain environmental conditions and target configurations, making even a reliably functioning capability still very fragile in operations.

It is likewise highly risky to pursue a countermeasures arms race. In the case of directed energy, the primary countermeasure is hardening. This might mean special filters or exotic window materials to counter HEL or thicker and heavier shielding to counter HPM. In addition to the direct physical cost of these types of countermeasures, they also tend to lead to degradation of the U.S. system's primary mission capability. For example, adding special features to a seeker may degrade its detection performance and thereby severely degrade the guided missile's effective range. Risking degradation of mission performance to counter a foreign weapon that is itself highly technically risky potentially hands the Chinese a victory without ever succeeding in their research program.

This situation is not all negative, however. The same technical risks that recommend against a U.S. arms race apply equally to the Chinese. It may turn out in the end that China's pursuit of directed energy is a net benefit to the U.S. if they expend significant effort, diverting resources from other lower-risk weapon technology, and never succeed in fielding an effective system.

V. Recommendations for Congress

Congress should frame its actions in response to a potential directed energy weapon threat with the objective of avoiding China gaining a strategic military advantage from such a weapon. This could be achieved by preventing or delaying China from getting such technology, but the same objective can be reached by negating the advantages of having such a weapon. Two of the recommendations I provide here bound these extreme options, and a third suggests a strategy to determine which is the best approach.

Delay: A New Look at Export Control

As suggested previously in this testimony, the U.S. can control very few technologies to slow Chinese HEL development. The U.S. should carefully monitor two remaining key enablers: computer models for predicting thermal flow in crystals, and instruments for measuring and characterizing extremely high powers. Congress should ensure that the Department of Defense has included related technology on its Military Critical Technologies List.

It is also important to understand what supporting procedures, such as for optics alignment, component cleaning, and thermal controls have been documented by the defense industry and government laboratories. While knowledge by itself cannot easily be transferred against one's will, documentation can. Documents themselves should be controlled, even if unclassified, and not authorized for public release. This could be particularly challenging for laboratories that value scholarly publication. Without proper guidance, it is doubtful that non-technical reviewers will appreciate the sensitivity of this supporting knowledge. Likewise this documentation when stored on unclassified computer systems is particularly vulnerable to cyber-theft. Congress should consider new policy to identify not just physical critical technologies but procedural and knowledge-based as well, and new approaches should be developed to promulgate this guidance beyond acquisition programs to more basic research institutions.

In this same spirit, national security could benefit across all disciplines and mission areas by revising the basic procedure for identifying critical technologies. To revisit the three categories of critical technology, they are fundamental knowledge, components and materials, and abstract enablers or "ilities". Current critical technology review largely focuses upon the first two categories, understandable because they are easy to define and attach a simple, succinct keyword descriptor. Unfortunately, in today's world of globalized technology, these keyword elements are so widely available that attempts to control them are naïve and futile. I have personally witnessed situations in which U.S. weapon programs have been essentially "reverse-ITARed" by missing out on access to better performing technology that was available from foreign sources, but the program could not access it, because it was considered a protected critical technology. There is a risk of this reverse-ITAR process happening in the HEL domain, specifically related to access to laser crystals. As an aside, Congress should be commended on the strategic importance it has placed on protecting U.S. access to rare earth elements and should continue and strengthen these initiatives.

Congress should consider directing the Department to explore a completely new approach to identification of critical technology. The new approach is inherently more complex and needs to be applied based upon weapon areas, rather than technologies. A full description of the procedure is beyond the time available in this hearing, but it involves decomposing the core capabilities that make up a weapon system and then mapping them back to the three categories of critical technology. Then these enabling technologies are compared against what is openly available on the global market to determine if they are critical. My hypothesis is that the vast majority of truly critical technologies fall into the third category of abstract enabling procedures. Rather than a potentially disruptive wholesale revamping of export control, it is recommended that Congress charter a pilot project to refine and assess this new approach to critical technology review, beginning with one of the advanced technologies that are the subject of this hearing.

Negate: Agile System of Systems Weapons Strategies

As discussed earlier, getting into a directed energy arms race is highly unadvisable. Instead, the Department should consider new approaches to developing and fielding weapon systems. Rather than high-value, monolithic capabilities sharing common failure modes that lead to widespread threat from directed energy weapons, the Department should pursue a strategy of diversity and speed.

Swarms of low-cost systems deployed in large numbers are a starting point, but as discussed earlier, even swarms themselves are not that effective against directed energy if they share a common failure mode. Instead these swarms need to include a wide-ranging mix of capabilities that complicate China's use of directed energy. For example, consider low-cost missiles launched toward a target in large numbers. If they included a mix of optical seekers in different wavelength bands, they could include filters outside their primary bands that hardened them to HEL without degrading performance. There could also be RF seekers included in the mix. For the Chinese to defeat this full range of capabilities with HEL, they would either need a very large number of lasers designed at different performance points or one very large and sophisticated laser well beyond what they can currently produce, potentially becoming cost-prohibitive.

The Department should also develop its capabilities faster with shorter, more incremental programs. This allows each cycle to respond to the status of the threat. Rather than attempt to predict 20 or 30 years out what Chinese advanced weapon capability will be then, the Department should attempt to field new systems that can take a short-term threat into account.

Both of these strategies are captured in the latest National Defense Authorization Act[24]. This law challenges the department to develop new acquisition practices, including new interoperability approaches and system engineering technology, that can lead to this vision of agile,

[24] National Defense Authorization Act for Fiscal Year 2017: Report (to Accompany S. 2943) on to Authorize Appropriations for Fiscal Year 2017 for Military Activities of the Department of Defense and for Military Construction, to Prescribe Military Personnel Strengths for Such Fiscal Year, and for Other Purposes, Together with Additional and Minority Views. , 2016. Print.

heterogeneous weapon systems. If the U.S. can field new technology that negates the effectiveness of Chinese directed energy capability at the time of fielding, China ends up spending a tremendous amount of resources with little net capability to show for it.

Shape and Respond: Technology-Driven Intelligence and Cohesive Information Management

It is nearly impossible for us here today to predict exactly how the future of directed energy weapons will evolve. Even if the U.S. were successful in creating a more responsive acquisition environment, it loses utility if the U.S. lacks awareness of the true current status of Chinese technology. For example, how would we know if the Chinese suddenly had a breakout success with particle beam technology, which might require a completely different response than the HEL threat?

Despite its many strengths and successes, the U.S. intelligence community has historically been challenged by breakout technology surprises. This is partially systemic in the intelligence collection cycle as applied to Science and Technology Intelligence (S&TI). All intelligence collection begins with an identified intelligence priority, but for esoteric technology matters, the nuance of the core intelligence collection priority is often lost in these requirements. These requirements then go to collectors, and scientific analysts interpret collected data. The process is very efficient and accurate when requirements generators know what to look for, but it breaks when one does not know what new discovery, technology, or experiment might lead to a breakout capability.

Congress can help address this challenge by directing the intelligence community to conduct a pilot project on technology-driven collection. Instead of beginning with an intelligence requirement, this approach begins with our own scientific research targeted at learning what indicators of new results point to breakouts. These indicators can then be provided to requirements officers who can place them into the traditional intelligence cycle. This modified science-driven intelligence cycle could benefit many disciplines, but directed energy is an excellent candidate upon which to focus this pilot.

Finally it may be possible to shape a desirable future with respect to directed energy weapons, but only if we as a nation know what we want that future to be. This begins with an understanding of what is in our own best interest. If we conduct a very thorough analysis of our current and planned warfighting capability and determine we are highly vulnerable to directed energy, then we want to do everything in our power to discourage a directed energy arms race. On the contrary, if we determine that overall we are quite resilient to advances in directed energy threats, then we may not care if the future is full of directed energy weapon systems. In fact we may even want to take actions to encourage this future, as adversaries may wind up spending tremendous resources on capabilities that provide them little strategic advantage.

This strategy begins with that assessment of U.S. weapon capability compared with a scientifically-driven assessment of threat effects. While similar on the surface with the current

JCIDS[25] requirements process, it differs in that the Joint Capabilities Integration and Development System, or JCIDS, generates threat requirements pairwise between a particular U.S. weapon system and a specific threat. If it is deemed a serious threat, the program is required to mitigate it. Otherwise it is ignored. I am suggesting that a much more holistic threat requirements approach is needed to look at overall vulnerabilities and advantages across the force structure.

Once this threat requirements process has identified a desired end-state, this must be mapped back to acquisition priorities. For example, if we are resilient to future HEL weapons and want China to invest in vain, what can we do programmatically to encourage their strategy? Should we invest differently? How do we design program protection and public relations plans so that we send messages that shape Chinese behavior to the most positive future end-state? And if we were successful in developing this type of strategic approach to acquisition, we would also need to have focused intelligence collection to provide feedback on its effectiveness.

To the best of my knowledge, no extensive strategic planning activities of this nature exist anywhere within government. Directed energy would provide an excellent domain to explore how this type of strategic planning can be accomplished. Congress should consider chartering a study to determine the best approach for executing such a process. The study should address who should lead the process, what organizations are needed to participate, and if there are additional authorities needed to execute it. If successful, the result would enable the U.S. to stay ahead of all future threats, to include the threat from Chinese advanced weapon technology.

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25 "JCIDS Manual." (n.d.): n. pag. United States Department of Defense, 18 Dec. 2015. Web. 14 Feb. 2017. <https://dap.dau.mil/policy/Documents/2015/JCIDS_Manual_with_errata_through_20151218.pdf>.